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# **Architecture and impacts of electric vehicles**

**Ioannis Moutafidis**

SID: 3302100011

SCHOOL OF SCIENCE & TECHNOLOGY

A thesis submitted for the degree of

*Master of Science (MSc) in Energy Systems*

SEPTEMBER 2011

THESSALONIKI – GREECE



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## **DISCLAIMER**

This dissertation is submitted in part candidacy for the degree of Master of Science in Energy Systems, from the School of Science and Technology of the International Hellenic University, Thessaloniki, Greece. The views expressed in the dissertation are those of the author entirely and no endorsement of these views is implied by the said University or its staff.

This work has not been submitted either in whole or in part, for any other degree at this or any other university.

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Name: .....

Date: .....

# Abstract

This dissertation was written as a part of the MSc in Energy Systems at the International Hellenic University. A short summary of the dissertation.

This target of this study was to provide a knowledge base for modern electric vehicles. This knowledge base includes components, subsystems, energy management, infrastructure and emissions. Moreover, a basic comparison on the efficiency of three innovating cars of the last year is made. Finally, it provides an outlook for the future development of electric vehicles and their systems.

Special thanks are given to my supervisor Dr. Leonidas Ntziachristos for his help during the production and completion of this dissertation. Also I would like to give thanks to Petros Katsis for his assistance in the making of the comparison chapter.

Ioannis Moutafidis

10/10/2011

# Contents

<b>DISCLAIMER .....</b>	<b>III</b>
<b>ABSTRACT .....</b>	<b>IV</b>
<b>CONTENTS .....</b>	<b>V</b>
<b>1 INTRODUCTION .....</b>	<b>1</b>
1.1 TRANSPORTATION HISTORY .....	1
1.2 FOSSIL FUEL SITUATION .....	2
1.3 EMISSIONS .....	4
1.4 ELECTRIC AND HYBRID ELECTRIC CARS.....	5
1.5 DESCRIPTION OF CHAPTERS.....	7
<b>2 HYBRID ELECTRIC VEHICLES SUBSYSTEMS DESCRIPTION .....</b>	<b>8</b>
2.1 ENERGY STORAGE SYSTEMS .....	9
2.1.1 <i>Lead-Acid Batteries.....</i>	<i>10</i>
2.1.2 <i>Nickel-Metal Hydride (NiMH) Batteries.....</i>	<i>11</i>
2.1.3 <i>Lithium-Ion Batteries .....</i>	<i>12</i>
2.1.4 <i>Nickel-Zinc (Ni-Zn) Batteries .....</i>	<i>13</i>
2.1.5 <i>Nickel-Cadmium (Ni-Cd) batteries .....</i>	<i>14</i>
2.1.6 <i>Ultracapacitors ( electric double-layer capacitor) .....</i>	<i>15</i>
2.1.7 <i>Fuel cells.....</i>	<i>18</i>
2.1.8 <i>Power requirements for batteries in hybrid electric vehicles ....</i>	<i>20</i>
2.2 DRIVETRAIN ARCHITECTURE.....	25
2.2.1 <i>Series hybrid electric vehicles.....</i>	<i>25</i>
2.2.2 <i>Parallel hybrid electric vehicles .....</i>	<i>27</i>
2.2.3 <i>Power-split hybrid electric vehicles .....</i>	<i>29</i>
2.2.4 <i>Choice of the appropriate architecture and other requirements</i>	<i>32</i>
2.3 ENERGY MANAGEMENT .....	35
2.4 CHARGING PROFILE .....	40
2.4.1 <i>State of the art for ESS charging systems .....</i>	<i>40</i>

2.4.2	<i>Requirements of the energy storage systems charging system design based on PHEV vehicle-level attributes.....</i>	<i>43</i>
2.4.3	<i>Constraints on vehicle-level design based on energy storage system charging characteristic attributes .....</i>	<i>43</i>
2.4.4	<i>Constraints on system-level design based on energy storage system charging characteristic attributes .....</i>	<i>44</i>
<b>3</b>	<b>PRESENTATION OF MODELS .....</b>	<b>45</b>
3.1	CHEVROLET VOLT.....	46
3.1.1	<i>Specifications .....</i>	<i>47</i>
3.2	NISSAN LEAF.....	55
3.2.1	<i>Specifications .....</i>	<i>56</i>
3.3	TOYOTA PRIUS (XW30) .....	59
3.3.1	<i>Toyota Hybrid Synergy Drive.....</i>	<i>60</i>
3.3.2	<i>Specifications .....</i>	<i>65</i>
<b>4</b>	<b>COMPARISON .....</b>	<b>66</b>
<b>5</b>	<b>IMPACTS AND FUTURE OF ELECTRIC VEHICLES .....</b>	<b>72</b>
5.1	EMISSIONS.....	72
5.1.1	<i>Formation of GHG emission from EV fuel cycles .....</i>	<i>74</i>
5.2	CHARGING INFRASTRUCTURE .....	77
5.2.1	<i>Charging modes for conductive charging .....</i>	<i>78</i>
5.2.2	<i>Inductive charging .....</i>	<i>85</i>
5.3	ECONOMY .....	85
5.4	OUTLOOK.....	88
5.4.1	<i>Energy storage devices .....</i>	<i>89</i>
5.4.2	<i>Electric propulsion motors .....</i>	<i>92</i>
5.4.3	<i>Power electronics .....</i>	<i>92</i>
5.4.4	<i>Other technological challenges .....</i>	<i>94</i>
	<b>BIBLIOGRAPHY -REFERENCES .....</b>	<b>95</b>

# 1 Introduction

## 1.1 Transportation history

Transportation has been a major part of human civilization since the dawn of time and will definitely continue to be one of the cornerstones of human society well into the future. Humans' first means of transport were walking and swimming. The domestication of animals introduces a new way to lay the burden of transport on more powerful creatures, allowing heavier loads to be hauled, or humans to ride the animals for higher speed and duration. Inventions such as the wheel and sled helped make animal transport more efficient through the introduction of vehicles. Also water transport, including rowed and sailed vessels, dates back to time immemorial, and was the only efficient way to transport large quantities or over large distances prior to the Industrial Revolution.

The first forms of road transport were horses, oxen or even humans carrying goods over dirt tracks that often followed game trails. Paved roads were built by many early civilizations, including Mesopotamia and the Indus Valley Civilization. The Persian and Roman empires built stone-paved roads to allow armies to travel quickly. Deep roadbeds of crushed stone underneath ensured that the roads kept dry. The medieval Caliphate later built tar-paved roads. The first watercraft were canoes cut out from tree trunks. Early water transport was accomplished with ships that were either rowed or used the wind for propulsion, or a combination of the two. The importance of water has led to most cities, that grew up as sites for trading, being located on rivers or at sea, often at the intersection of two bodies of water. Until the Industrial Revolution, transport remained slow and costly, and production and consumption were located as close to each other as feasible.

The Industrial Revolution in the 19th century saw a number of inventions fundamentally change transport. With telegraphy, communication became instant and independent of transport. The invention of the steam engine, closely followed by its application in rail transport, made land transport independent of

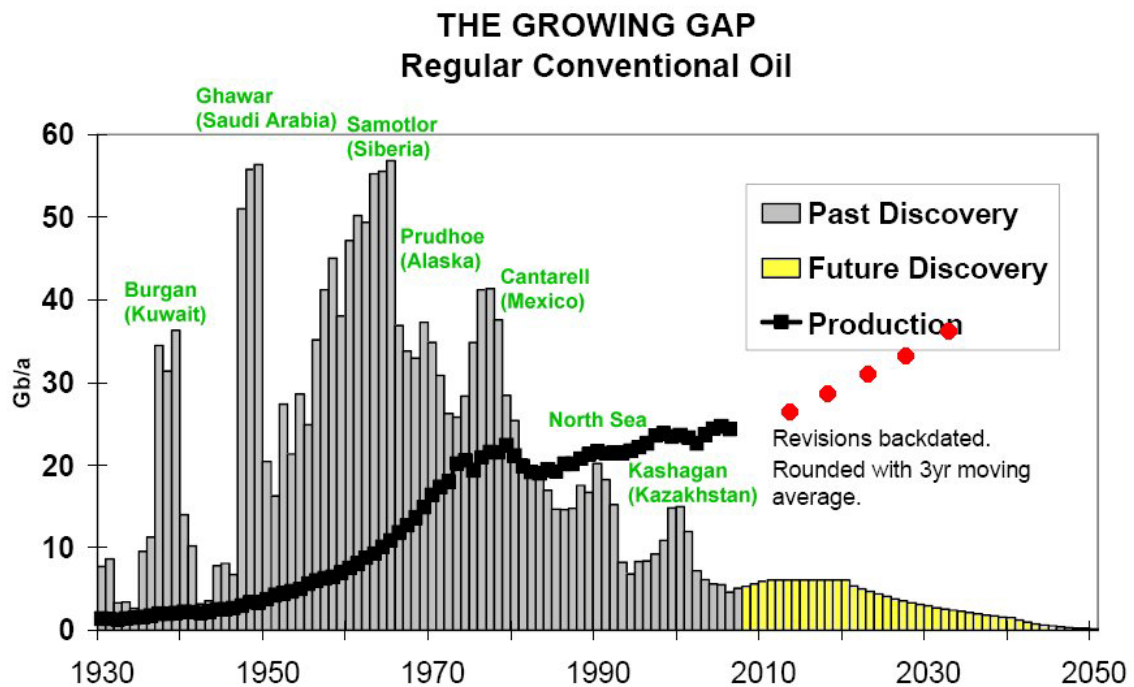
human or animal muscles. Both speed and capacity increased rapidly, allowing specialization through manufacturing being located independent of natural resources. The 19th century also saw the development of the steam ship, that sped up global transport.

With the development of the combustion engine and the automobile at the turn into the 20th century, road transport became more viable, allowing the introduction of mechanical private transport. The internal combustion engine is an engine in which the combustion of a fuel (normally a fossil fuel) occurs with an oxidizer (usually air) in a combustion chamber. In an internal combustion engine, the expansion of the high-temperature and -pressure gases produced by combustion applies direct force to some component of the engine, such as pistons, turbine blades, or a nozzle. This force moves the component over a distance, generating useful mechanical energy.

## **1.2 Fossil fuel situation**

However, fossil fuels are a finite resource, a fact that has been even more realized in the last decades. Fig. 1 shows oil discoveries and oil consumption since 1930 to 2008. The black line shows oil consumption. Notice the peak in consumption in 1979 corresponding to the first oil crisis. The subsequent 5 year decline in oil consumption is attributed to more fuel efficient transportation and a slowing world economy. The grey bars show oil discoveries. Notable grey bar features include Kuwait's big oil field, Burgan, which was discovered in the late 30s and Ghawar, the world's largest oil field, which was discovered in 1948. Note that the discovery rate peaked around 1966. Note also that consumption exceeds discoveries every year since 1984. Now there is a large gap between discoveries and production. None of this is controversial--it is only history[1].





**Figure 1** Growing gap between oil discovery and production.

What happens after 2008 is extrapolation and speculation. The EIA [2](Energy Information Agency) has projected a 1.6% annual growth in oil demand which is shown in red. Developed countries, for example the USA, Germany and Japan are not expected to increase consumption. In fact, consumption might decrease because of efficiency gains. But China and India both have booming economies. Automobile ownership increased by 37% in China and 17% in India in 2007. The yellow bars represent a guess about yet-to-find oil. The yellow bars show no declines in the discovery rate until 2021. That seems optimistic given the declining discovery rate in the previous decade. Note the growing gap between discoveries and production!

Oil discovered 40 years ago is the basis of current oil production. The search for oil continues but projected oil discoveries will contribute little to projected oil production in 2030. The declining rate of oil discoveries makes it painfully obvious--most of the oil has already been discovered. The technology for finding oil has improved greatly since the major discoveries, yet little oil has been found in recent years. The heyday of oil discovery was from 1950 to 1980. It is difficult to avoid the conclusion--most of the oil has been found. *There is a growing gap between discoveries and production.*

World oil production is running flat out. Only the Saudi Arabian claim to have the ability to produce more though some dispute this. It is not a simple matter of turning a spigot or pumping faster. Oil fields can be permanently damaged by attempting to produce too fast. *Soon there will be a gap between production and demand.*

### **1.3 Emissions**

Moreover, there is another problem with conventional cars and that is emissions. Emissions from motor vehicles have become a major problem. Many consumers don't know the effects of motor vehicle emissions. Most consumers don't take emissions testing seriously, but it's a necessity in helping save the environment. There are many emissions issues consumers don't know, and issues they should know. Cars emit harmful pollutants that can affect the environment, and the American public's health.

According to the US Environment Protection Agency (EPA), driving a car is the single most polluting thing most of us do. Motor vehicles emit millions of tons of pollutants into the air every day. In many urban areas motor vehicles are the single largest contributors of ground level ozone, a major component of smog. Motor vehicles generate three major pollutants, nitrogen oxides, hydrocarbons, and carbon monoxide. Hydrocarbons react with nitrogen oxides in the presence of sunlight and elevated temperatures to form ground level ozone. It can cause eye irritation, coughing, wheezing, and shortness of breath. Can lead to permanent lung damage. Nitrogen oxides contribute to acid rain, and to water quality problems. Carbon monoxide is a colorless, odorless, deadly gas. It reduces the flow of oxygen to the bloodstream, and can impair mental functions and visual perception. In urban areas emissions from vehicles are responsible for more than 90 percent of carbon monoxide in the air. Motor vehicles also emit large amounts of carbon dioxide, which has potential to trap the Earth's heat and cause global warming[3].

Cars release pollutants from the tailpipe as the result of the fuel combustion process, and from under the hood throughout the fuel system when heat causes fuel evaporation. Evaporative emissions occur when hot temperatures outside cause a car's fuel to evaporate, when the hot engine, and exhaust system of a

running car cause the fuel to become heated. When the car is turned off, it remains hot enough to cause fuel to evaporate. This also happens during refueling when gasoline vapors escape into the air from the gas tank, and nozzle. The greatest amount of pollutants is released during the “cold start,” or the first few moments of the warm up phase.

## **1.4 Electric and hybrid electric cars**

The above problems with the electric cars and the advance of human technology have led scientists and manufactures to look for other forms of powering vehicles. This search has led to one of the cleanest forms of energy, electricity.

An electric vehicle (EV), also referred to as an electric drive vehicle, uses one or more electric motors or traction motors for propulsion. Three main types of electric vehicles exist, those that are directly powered from an external power station, those that are powered by stored electricity originally from an external power source, and those that are powered by an on-board electrical generator, such as an engine (a hybrid electric vehicle), or a hydrogen fuel cell. Electric vehicles include electric cars, electric trains, electric lorries, electric airplanes, electric boats, electric motorcycles and scooters and electric spacecraft.

Electric cars have several potential benefits as compared to conventional internal combustion automobiles that include a significant reduction of urban air pollution as they do not emit harmful tailpipe pollutants from the onboard source of power at the point of operation (zero tail pipe emissions); reduced greenhouse gas emissions from the onboard source of power depending on the fuel and technology used for electricity generation to charge the batteries; and less dependence on foreign oil, which for the United States, other developed and emerging countries is cause of concerns about their vulnerability to price shocks and supply disruption. Also for many developing countries, and particularly for the poorest in Africa, high oil prices have an adverse impact on their balance of payments, hindering their economic growth.

A hybrid electric vehicle (HEV) is a type of hybrid vehicle and electric vehicle which combines a conventional internal combustion engine (ICE) propulsion system with an electric propulsion system. The presence of the electric powertrain is intended to achieve either better fuel economy than a conventional ve-

hicle, or better performance. A variety of types of HEV exist, and the degree to which they function as EVs varies as well. The most common form of HEV is the hybrid electric car, although hybrid electric trucks (pickups and tractors) and buses also exist.

Modern HEVs make use of efficiency-improving technologies such as regenerative braking, which converts the vehicle's kinetic energy into electric energy to charge the battery, rather than wasting it as heat energy as conventional brakes do. Some varieties of HEVs use their internal combustion engine to generate electricity by spinning an electrical generator (this combination is known as a motor-generator), to either recharge their batteries or to directly power the electric drive motors. Many HEVs reduce idle emissions by shutting down the ICE at idle and restarting it when needed; this is known as a start-stop system. A hybrid-electric produces less emissions from its ICE than a comparably-sized gasoline car, since an HEV's gasoline engine is usually smaller than a comparably-sized pure gasoline-burning vehicle (natural gas and propane fuels produce lower emissions) and if not used to directly drive the car, can be geared to run at maximum efficiency, further improving fuel economy.

There three major types of electric vehicles in the market. Battery electric vehicles, which use only electric energy from the grid for propulsion, hybrid electric vehicles, which use both electric energy and fossil fuels to generate energy for propulsion and fuel cell electric vehicles that use hydrogen fuel cells to power the motor drives. Table 1 shows the major characteristics of these three types of vehicles.

**Table 1** Major characteristics of BEV, HEV and FCEV.

Types of EVs	Battery EVs	Hybrid EVs	Fuel cell EVs
<b>Propulsion</b>	Electric motor drives	Electric motor drives Internal combustion engine	Electric motor drives
<b>Energy system</b>	Battery Ultracapacitor	Battery Ultracapacitor ICE generating unit Integrated starter generator	Fuel cells Need battery/ultracapacitor to enhance power density for starting
<b>Energy sources and infrastructure</b>	Electric grid charging facilities	Gasoline stations Electric grid charging facilities(for PHEVs)	Hydrogen Hydrogen production and transportation infrastructure
<b>Characteristics</b>	Zero emission Independence on crude oils High energy efficiency  High initial cost Commercially available Relatively short range	Very low emissions Long driving range Higher fuel economy as compared with ICE vehicles  Dependence on crude oils Complex Commercially available	Zero emission or ultra low emission Higher energy efficiency Independence on crude oils  Satisfied driving range High cost Under development
<b>Major issues</b>	Battery and battery management High performance propulsion Charging facilities	Managing multiple energy sources Dependent on the driving cycle Battery sizing management	Fuel cell cost Hydrogen infrastructure Fueling system

## 1.5 Description of chapters

The target of this thesis is to provide knowledge on modern electric vehicles including their architecture, their components and the impacts of their use for modern human society. Also a comparison between three different manufacturer concepts is provided.

Chapter 2 describes the architecture and subsystems of hybrid electric vehicles. It describes the energy storage systems, the drivetrain configurations,

the energy management strategies and the charging profiles. The only difference with BEVs is the drivetrain because BEVs have simpler architecture since they use one form of energy.

Chapter 3 describes the three models that will be compared in the following chapter. These three models are Chevrolet Volt (or Opel Ampera in Europe), Nissan Leaf and Toyota Prius (third generation XW30).

In chapter 4 a comparison on the efficiency is presented.

Chapter 5 presents some of the impacts of the introduction and usage of electric vehicles as a transportation mean and some thoughts on the future of this technology.

## **2 Hybrid electric vehicles subsystems description**

Hybrid electric vehicles are relatively new in the market of commercial cars but some of the parts used in their construction are well known. In this chapter the main parts of electric vehicles are described. There is not a different chapter for hybrid electric vehicles and plug-in hybrid electric vehicles because the design is very similar, however this dissertation is more focused on plug-in hybrid electric vehicles.

The design of any complicated system including plug-in hybrid electric vehicles is complex, multiobjective, and iterative. Further complicating the analysis of design of these commercial products is that the details of commercial design processes are generally not published. Research into design methods is therefore necessarily reductionist; we cannot describe the entire complexity of the design process, instead we must understand and describe the its primary elements.

## 2.1 Energy Storage Systems

The fuel economy and all electric range of hybrid electric vehicles are highly dependent on the onboard energy storage system of the vehicle. Hybrid electric vehicles obviously required energy storage system with different characteristics from conventional vehicles. Electric vehicle batteries differ from starting, lighting and ignition (SLI) batteries because they are designed to give power over longer sustained periods of time. Deep cycle batteries are used instead of SLI batteries for these applications. Batteries for electric vehicles are characterized by their relatively high power-to-weight ratio, energy to weight ratio and energy density; smaller, lighter batteries reduce the weight of the vehicle and improve its performance. Energy storage devices charge during low power demands and discharge during high power demands, acting as catalysts to provide energy boost. Increasing the all electric range of vehicles by 15% almost doubles the incremental cost of energy storage systems. This is due to the fact that the energy storage system of hybrid electric vehicles requires higher peak power while preserving high energy density [4].

Typically electrochemical energy storage for hybrid electric vehicles consists of battery packs, although battery/ultracapacitor and regenerative fuel cell hybrid electric vehicles have been proposed. The energy storage system (ESS) consist of the battery modules and their support systems including thermal management, electrical management and safety subsystems. The purpose of the energy storage systems for hybrid electric vehicles is to accumulate electric energy for propulsion and to meet some short term power demands of the vehicle. These short-term power demands can be charging the energy storage system in the case of regenerative braking, or they can be discharging the energy storage system, in the case of vehicle accelerations. The batteries of hybrid electric vehicles must perform these functions at a variety of states of charge (SOC). Depending on the characteristics of the vehicle, the electrical energy stored can commonly be as large as 19 kWh with power transients of >75kW for a mid-sized sedan, or 30 kWh and >150kW for a full-size sport utility vehicle (SUV).

There is a number of technologies in the battery design and construction and each has different characteristics. The manufacturer chooses what is the most appropriate for the configuration.

### **2.1.1 Lead-Acid Batteries**

The spongy lead acts as the negative material of the battery, lead oxide is the positive active material and diluted sulfuric acid is the electrolyte. When discharging, both positive and negative materials are transformed into lead sulfate. The lead-acid battery has a number of advantages for hybrid electric vehicle applications. There is an availability for production volumes in the present day, yielding a relatively low cost power source. Additionally, lead-acid technology is an established technology due to its wide use over the past 50 years. Nevertheless, the lead-acid battery is not appropriate for discharges over 20% of its related capacity. When operated at a deep rate of state of charge the battery would have a limited life cycle. The energy and power density of the battery is low due to the weight of lead collectors. Research efforts have found that energy density can be improved by using lighter noncorrosive collectors. Below on fig. 2 is a typical lead acid battery.





**Figure 2** lead acid battery.

### **2.1.2 Nickel-Metal Hydride (NiMH) Batteries**

The NiMH Battery uses an alkaline solution as the electrolyte. The NiMH battery is made of nickel hydroxide for the positive electrode, and the negative electrode consists of an engineered alloy of vanadium, titanium, nickel and other metals. The NiMH battery has double the energy density of the lead-acid battery. Moreover the elements of NiMH are harmless to the environment and the NiMH batteries can be recycled. The NiMH battery can be safely operated at high voltage and has evident advantages, such as storing volumetric energy and power, long cycle life, wide operation temperature ranges and a resistance to overcharge and discharge.

However, if repetitively discharged at high load currents, the operational life of NiMH is reduced to about 200-300 cycles [5]. The overall finest performance is accomplished when discharged 20% to 50% of the rated capacity. The memory effect in NiMH battery systems reduces the utilizable power of the hybrid electric vehicle, which decreases the usable state of charge of the battery to a quantity smaller than 100%. Below in fig. 3 is a NiMH battery of a Toyota Prius.



**Figure 3** High power Ni-MH Battery of Toyota NHW20 Prius, Japan.

### **2.1.3 Lithium-Ion Batteries**

The lithium-ion battery has been proven to have exceptional performance in portable electronics and medical devices [6]. The lithium-ion battery has high energy density, has good high temperature performance and is able to be recycled. The positive electrode is made of a oxidized cobalt material. The lithium salt in an organic solvent is used as the electrolyte. The promising features of the Li-ion batteries incorporate low memory effect, high specific power of 300W/kg, high specific energy of 100Wh/kg, and long battery life of 1000 cycles. These outstanding characteristics give the lithium-ion battery a high possibility of replacing NiMH as the next generation batteries for vehicles (something that already occurs in many new and upcoming vehicle models). The material and cell characteristics of various chemistries are presented in table 2.

**Table 2** Characteristics of lithium-ion batteries using various chemistries.

Chemistry Anode/Cathode	Cell voltage Max/nom.	Ah/gm Anode/Cathode	Energy density Wh/Kg	Cycle life (deep)	Thermal Stability
Graphite/ NiCoMnO <sub>2</sub>	4.2/3.6	0.36/0.18	100-170	2000-3000	fairly stable
Graphite/ Mn spinel	4.0/3.6	0.36/0.11	100-120	1000	fairly stable
Graphite/ NiCoAlO <sub>2</sub>	4.2/3.6	0.36/0.18	100-150	2000-3000	least stable
Graphite/ iron phosphate	3.65/3.25	0.36/0.16	90-115	>3000	stable
Lithium titanate/ Mn spinel	2.8/2.4	0.18/0.11	60-75	>5000	most stable

NiMH batteries were priced at about 1500\$/kWh in 2007. Given that the price of nickel is growing, the prospective of cost reduction of NiMH batteries is not promising. Li-ion batteries possess twice the energy density of NiMH batteries, and they are priced at 750\$ to 1000\$/kWh. Below in fig. 4 is a picture of Nissan Leaf Li-ion battery packs.



**Figure 4** Nissan Leaf's lithium-ion battery pack.

#### 2.1.4 Nickel-Zinc (Ni-Zn) Batteries

Nickel-zinc batteries possess high energy and power density, low cost materials and deep cycle capability and are environmentally friendly. The operational temperature of Ni-Zn batteries ranges from -10 °C to 50 °C, something that means that they are capable of operating under severe working circumstances. However they suffer from poor life cycles due to fast growth of dendrites, which

prevents the development of Ni-Zn batteries in vehicular applications[7]. In fig. 5 is a typical Ni-Zn battery.

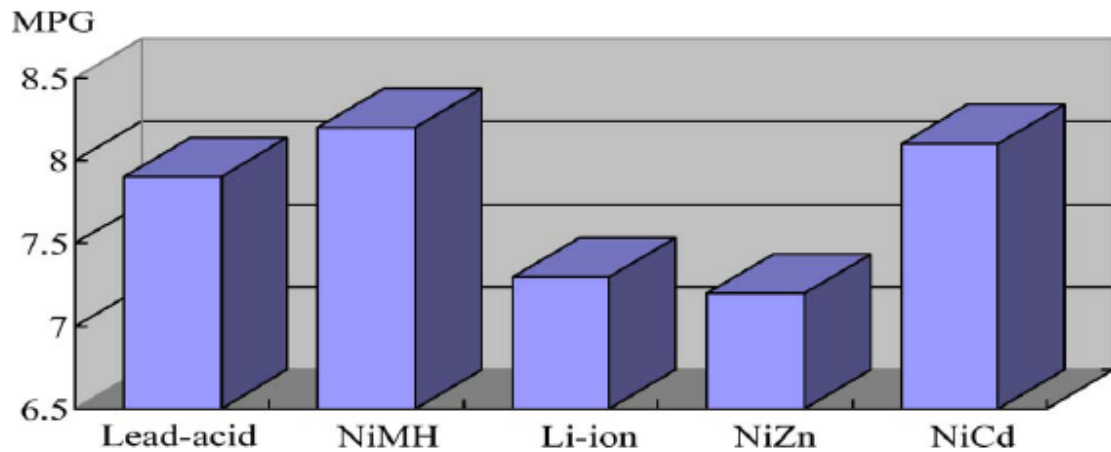


**Figure 5** Nickel Zinc battery.

#### **2.1.5 Nickel-Cadmium (Ni-Cd) batteries**

Nickel-cadmium batteries have a long lifetime and are able to be fully discharged without damage. The specific energy of Ni-Cd batteries is around 55 Wh/kg. These batteries are able to be recycled, however cadmium is a kind of heavy metal that could cause environmental pollution if not properly disposed of. One more drawback of Ni-Cd batteries is the cost. Typically, it will cost more than 20000\$ to install these batteries on vehicles[8],[9].

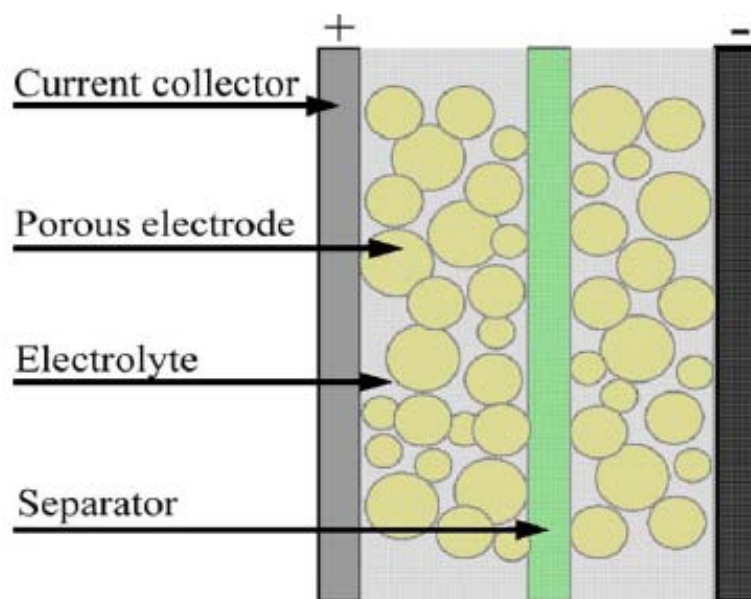
Fig. 6 show a comparison of fuel economy of separate batteries for a diesel-fueled transit bus in Indian urban driving cycles. This figure shows that the Ni-MH battery has the best fuel efficiency. However this is an older comparison and the Li-ion technology has improved since and it seems to be taking over the market.



**Figure 6** Fuel economy (in miles per gallon) comparison on different batteries.

### 2.1.6 Ultracapacitors ( electric double-layer capacitor)

The ultracapacitor stores energy by physically separating positive and negative charges. The charges are accumulated on two parallel plates divided by an insulator. Because there are no chemical variations on the electrodes, ultracapacitors have a long cycle life but low energy density. In fig. 7 the structure of an individual ultracapacitor cell is shown [10]. The applied potential on the positive electrode attracts the negative ions in the electrolyte, while the potential on the negative electrode attracts the positive ions.

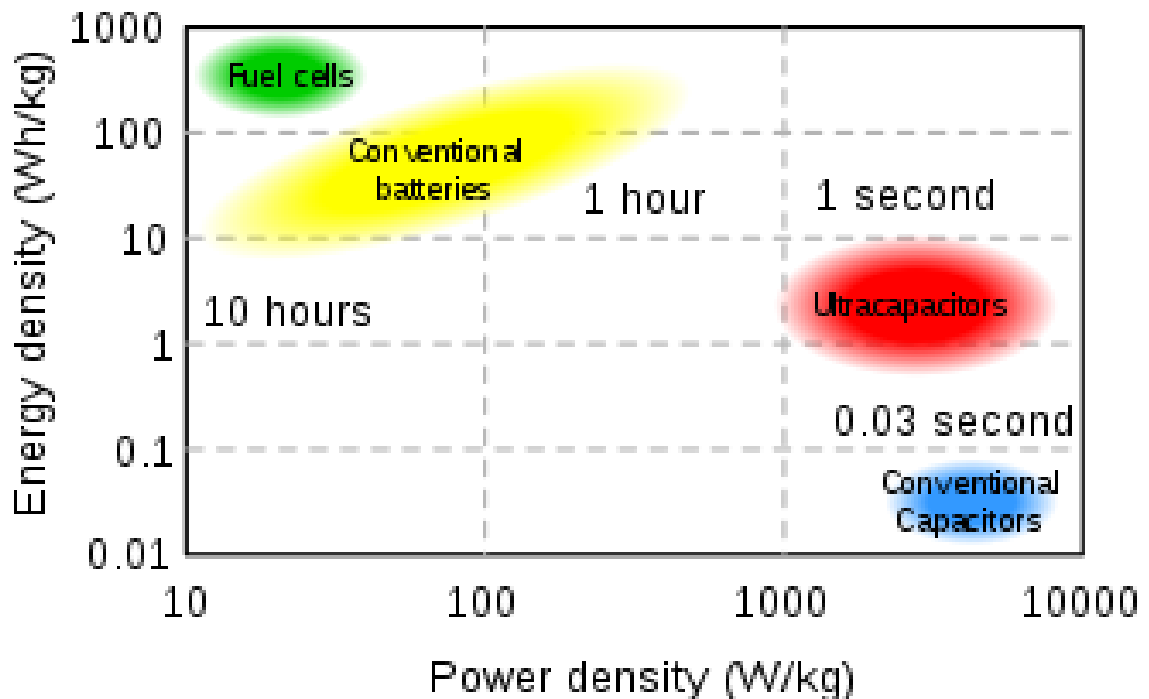


**Figure 7** Individual ultracapacitor cell.

The power density of the ultracapacitor is significantly higher than that of a battery. This is because of the fact that the charges are physically stored on the electrodes. The low internal resistance provides the ultracapacitor with high efficiency however it can cause a large burst of output currents in the event that the ultracapacitor is charged at a very low state of charge [11], [12].

One more characteristic of the ultracapacitor is the fact that the terminal voltage is directly proportional to the state of charge. The ultracapacitor is able to function throughout its variable voltage range with the development of interface electronics.

Ultracapacitors are used to provide assistance to the primary energy storage devices in the hybrid electric vehicles. The primary characteristic of urban driving is the many stop and go conditions with the total power that is required being fairly low. Ultracapacitors are exceptionally capable of capturing electricity from regenerative braking and quickly delivering power for acceleration owing to their rapid charge and discharge rates. In hybrid electric vehicle applications both batteries and ultracapacitors can be pooled to maximize the advantages of both components. There is an estimation that over 30000 ultracapacitors are at work in hybrid drives, providing over 75 million Farad of electric drive and regenerative braking power . In fig. 8 a chart is shown with a comparison of energy density versus power density for different energy storage devices.

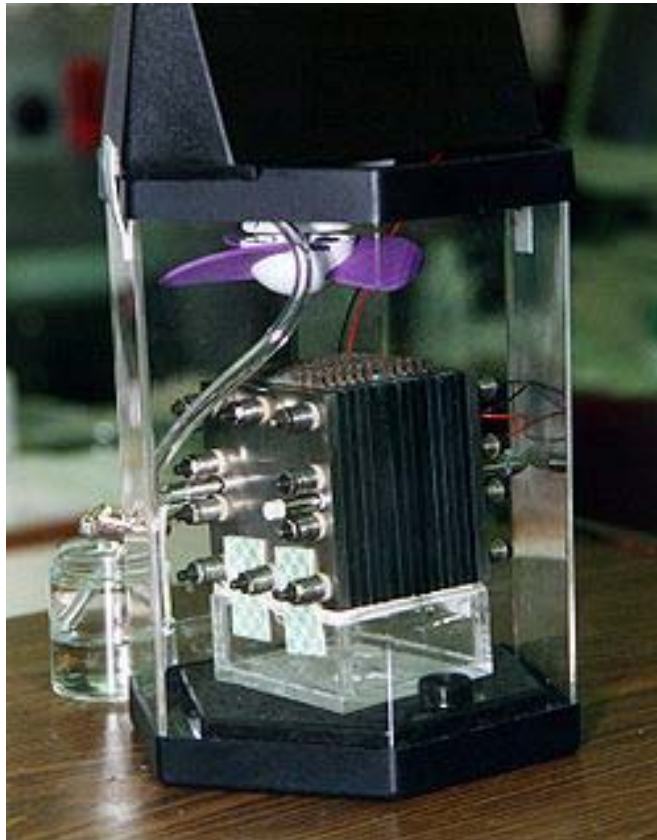


**Figure 8** Ragone chart showing energy density vs. power density for various energy-storage devices.

There are five ultracapacitor technologies in development: foamed carbon, carbon/metal fiber composites, a carbon particulate with a binder, doped conducting polymer films on a carbon cloth and mixed metal oxide coatings on a metal foil. Greater energy density can be accomplished with a carbon composite electrode using an organic electrolyte rather than a carbon/metal fiber composite electrode with an aqueous electrolyte, this kind of material is activated carbon from coconut shells.

Research in ultracapacitors focuses on improved materials that offer higher usable surface areas. The energy density of existing commercial ultracapacitors ranges from around 0.5 to 30 W·h/kg including lithium ion capacitors, known also as a "hybrid capacitor". Experimental ultracapacitors have demonstrated densities of 30 W·h/kg and have been shown to be scalable to at least 136 W·h/kg. Costs have fallen quickly, with cost per kilojoule dropping faster than cost per farad. As of 2006 the cost of supercapacitors was 1 cent per farad and \$2.85 per kilojoule, and was expected to drop further.

### 2.1.7 Fuel cells



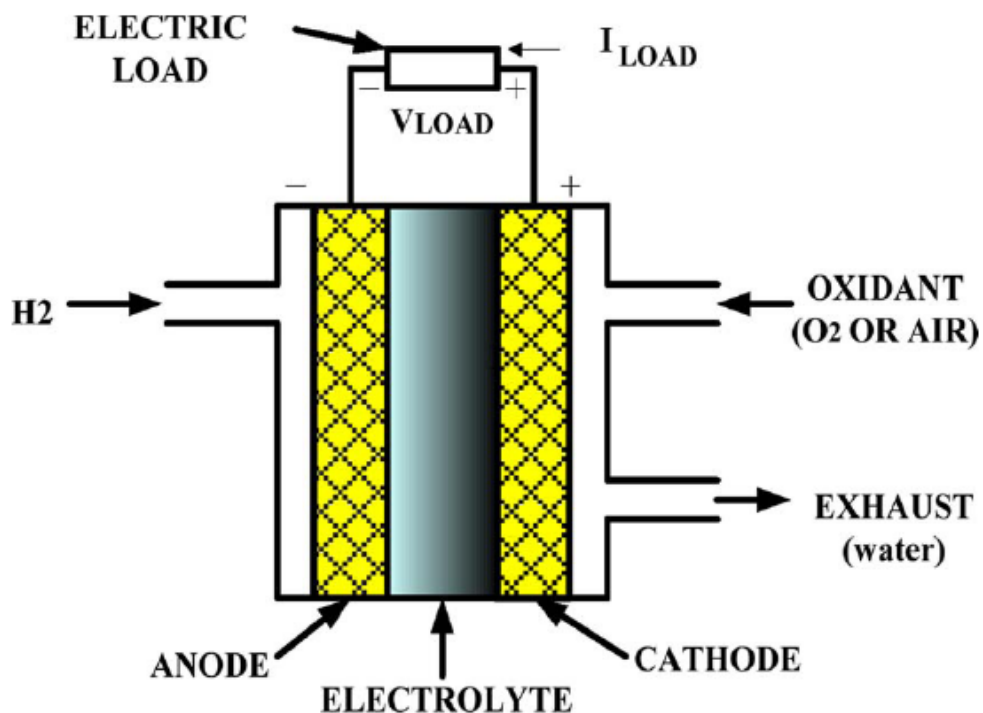
**Figure 9** Demonstration model of a direct-methanol fuel cell. The actual fuel cell stack is the layered cube shape in the center of the image.

A fuel cell is a device that converts the chemical energy from a fuel into electricity through a chemical reaction with oxygen or another oxidizing agent. Hydrogen is the most common fuel, but hydrocarbons such as natural gas and alcohols like methanol are sometimes used. Fuel Cells are different from batteries in that they require a constant source of fuel and oxygen to run, but they can produce electricity continually for as long as these inputs are supplied [Wikipedia].

The fuel cell produces electrical energy from the fuel on the anode and the oxidant on the cathode and the reacts in the electrolyte. Throughout the generation procedure, the reactants stream into the cell, while the products of the reaction gush out. The fuel cell is capable of generating electricity for as much time as the reactants stream is maintained. The advantages of the fuel cell involve quiet operation, high conversion efficiency of fuel to electrical energy, zero or very low emissions, fuel flexibility, waste heat recoverability, durability and reliability.



Fuel cells come in many varieties with different combinations of fuels and oxidants. An ideal nonpolluting fuel for fuel cells is hydrogen, because hydrogen possesses the highest energy density that any other fuel, moreover the outcome of the cell reaction is just water. An example of the configuration of a hydrogen fuel cell is shown in fig. 10 [13]. Among the other fuels hydrocarbons and alcohols are included, moreover additional oxidants include chlorine and chlorine dioxide [14].



**Figure 10** Configuration of a hydrogen fuel cell.

The difference with electrochemical batteries is that the reactants of the fuel cells must be replenished earlier than they are used up. For vehicular applications, a specific fuel tank must be included on board. However fuel cells have a relatively low energy density (2,6 kWh/L or liquid hydrogen compared to the 6 kWh/L of petrol), hence large fuel tanks are required[4].

The fuel cell efficiency depends on the amount of power extracted from it. Commonly, the more power extracted, the lower the efficiency. Most of the losses are exhibited as a voltage decline on the internal resistances. A disadvantage of fuel cells is that they have a relatively longer response time in comparison to that of batteries and ultracapacitors. One more negative aspect of

fuel cells is the fact that they are expensive. Presently fuel cells cost five times more than internal combustion engines, with the major cost components being the membrane, the electro catalyst and the bipolar plates. Moreover new research is currently undergoing in order to develop hydrocarbon membranes to substitute the current per fluorinated membranes [15]. Table 6 summarizes typical characteristics of fuel cells.

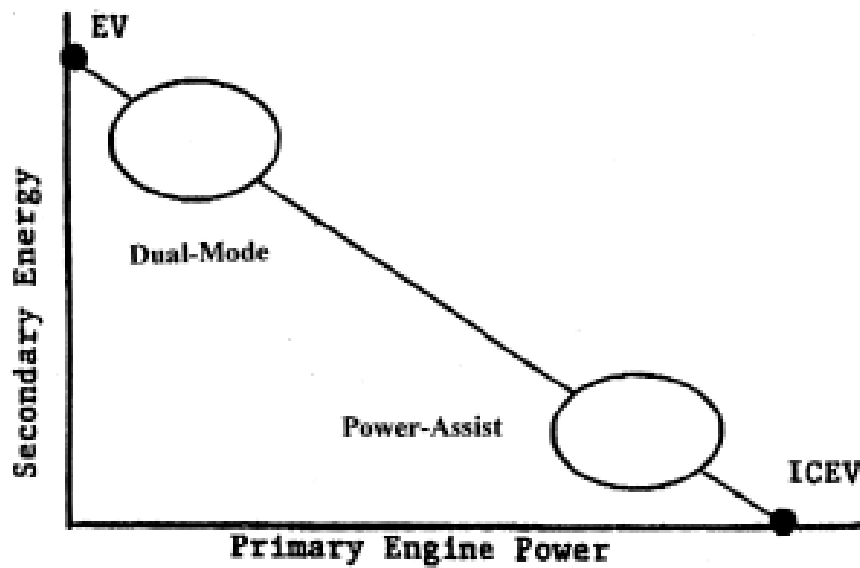
**Table 3** Typical characteristics of fuel cells.

	PAFC	MCFC	AFC	SOFC	DMFC	SPFC
<b>Temp (°C)</b>	150-210	600-700	60-100	900-1000	50-100	50-100
<b>Density (W/cm<sup>2</sup>)</b>	0.2-0.25	0.1-0.2	0.2-0.	0.24-0.3	0.04-0.23	0.35-0.6
<b>Life (kh)</b>	40	40	10	40	10	40
<b>Cost (\$/kW)</b>	1000	1000	200	1500	200	200
PAFC- phosphoric acid fuel cell MCFC- molten carbonate fuel cell AFC- alkaline fuel cell SOFC- solid oxide fuel cell DMFC- direct methanol fuel cell SPFC- solid polymer fuel cell also known as proton exchange membrane fuel cell						

### 2.1.8 Power requirements for batteries in hybrid electric vehicles

In very simple terms, a hybrid vehicle is a vehicle which has two discrete power sources, one normally being the primary and the second the auxiliary. The primary energy source is operated as much of the time as possible in its zone of maximum efficiency with some approximately constant output power level. When more power is required, the auxiliary power system is engaged. In a hybrid electric vehicle the primary source can be an internal combustion engine, or even a fuel cell and the auxiliary or secondary usually is some kind of energy storage device like a battery, which can provide and absorb high, short bursts of current. This mode is called “power-assist” and in this case the battery is comparatively smaller and is operated on a demand basis. Another configuration is a approximately equal sharing of power output by the primary and secondary sources, with the secondary being used more or less continuously; this design is called “dual-mode”. These two configurations lie between a pure heat-engine internal combustion engine vehicle (ICEV) and a zero-emission electric vehicle (ZEV), as show in fig. 11. During regenerative braking events the aux-

iliary power source absorbs the mechanical energy in the form of chemical energy that will later be turned to electricity, which is dissipated and lost in a conventional vehicle. When there is a need for extra power for either acceleration or hill climbing, power is drawn from the auxiliary power source in both architectures. Also a usual hybrid electric vehicle contains an electronic control module which is required to orchestrate the operation of the two power sources [16].

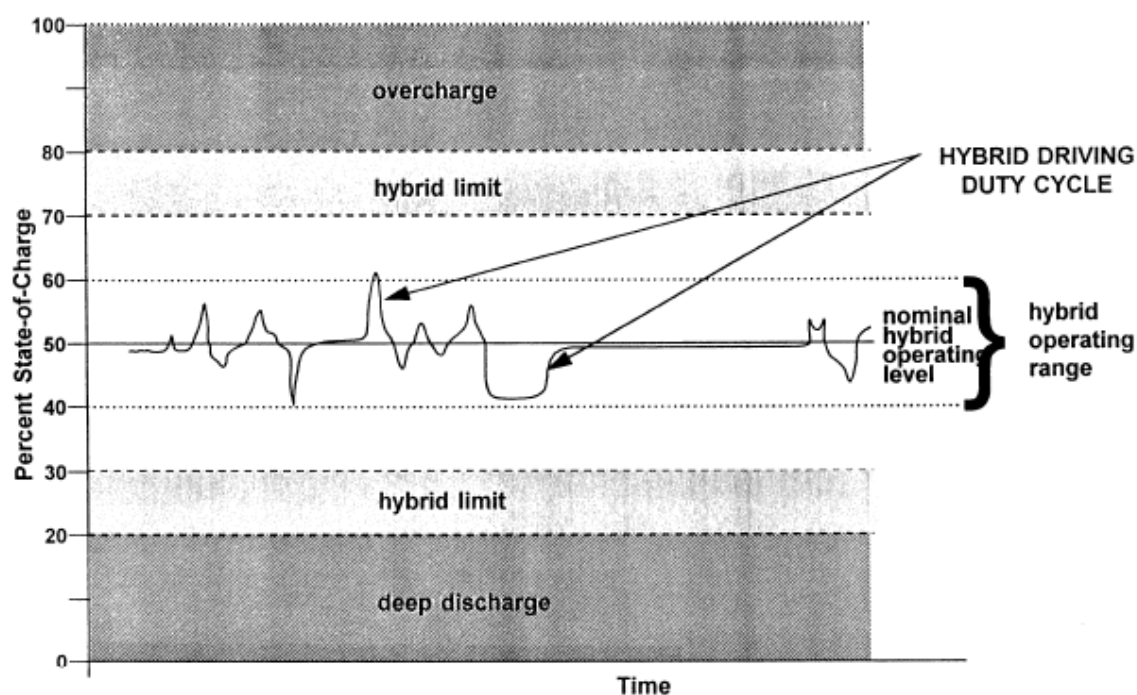


**Figure 11** Hybrid electric vehicle design spaces for power-assist and dual-mode batteries relative to electric vehicles (EV) and internal combustion engine vehicles (ICEV).

The type of operation of a hybrid vehicle places special requirements on the battery when it functions as the auxiliary power source. For the battery to maximize and optimize its operating life, it must spend minimal time in overcharge and/or over discharge. As was stated above, the battery must be capable of delivering and capturing large currents almost immediately whilst functioning from a baseline partial state of charge of approximately 50%. Hybrid electric vehicle batteries of current configurations have voltage rates of 100-300 V or even more. Moreover these batteries are large groups of series linked (also possibly parallel) cells or modules, as such it is possible for thermal issues to arise in their operation in a vehicle. Also because of the long string battery configuration, individual cell balance becomes a major issue. Even though each of these issues can be effectively resolved with the appropriate control systems, they must be kept at a minimum because otherwise the cost for these vehicles de-

signed for conventional uses will become a dominant issue. All the above demands necessitate an exceptional duty cycle on the battery, one that is not expected to be seen in any other commercial applications.

A qualitative representation of battery performance demands in a typical hybrid electric vehicle duty cycle is presented in fig. 12.

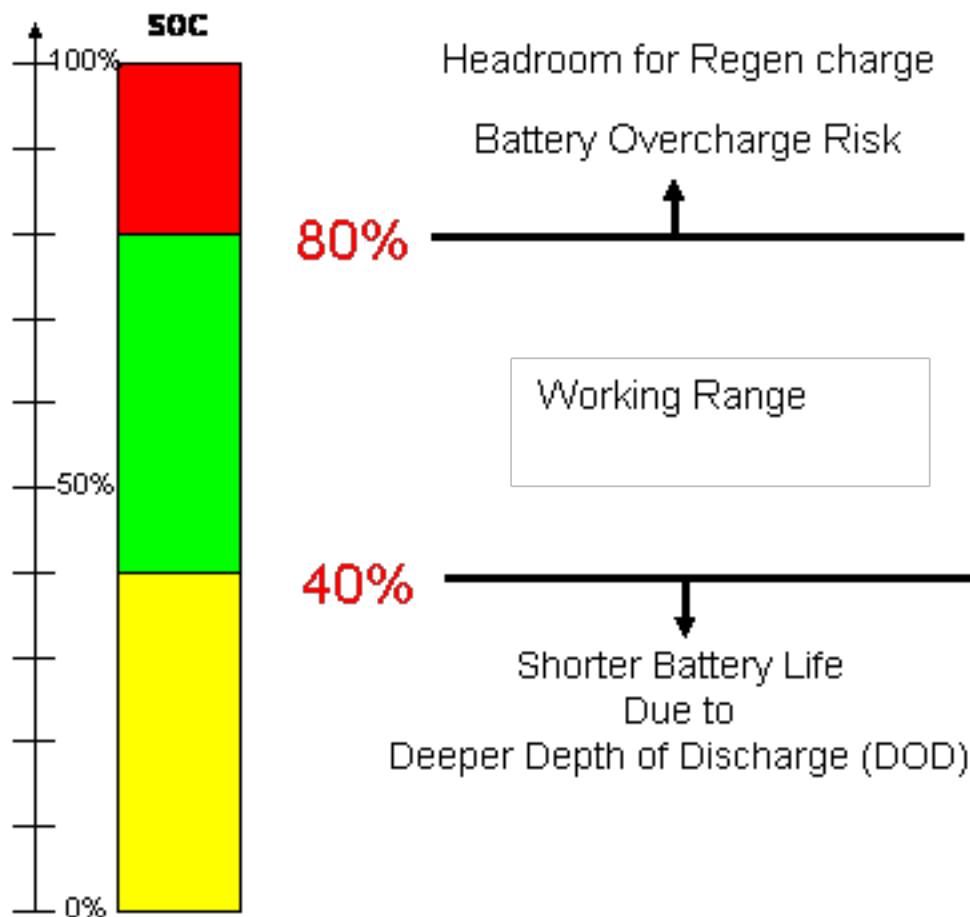


**Figure 12** State of charge considerations for battery operation in hybrid electric vehicles.

The battery is managed at a nominal state of charge level near 50% so that it can be able to deal with charge or discharge current surges without moving into overcharge (above  $\approx 80\%$  state of charge), deep discharge (below  $\approx 20\%$  state of charge) or over discharge (below 0%). Since these large current spikes will have a great tendency to drive the battery high and low, a pragmatic operating window for hybrid electric vehicle operation is more like 30-70% state of charge as shown. If this window is stretched a bit to 25-75%, it is seen that only roughly half of the battery's rated capacity is operated. Therefore, the functional capacity of a hybrid electric vehicle is only one half of the normal rated capacity. This realization means that if "x" kWh is required for hybrid electric vehicle operation, then a battery with "2x" rated capacity must be sized for the application. If a battery is greater on discharge than on charge acceptance, a nominal level of somewhat below 50% state of charge would be used. Conversely, a level of

above 50% would be chosen if charge acceptance were better than discharge. The nominal operating level of the hybrid is chosen based upon the charge-delivery and charge-acceptance characteristics of the electrochemistry and battery type being used in the vehicle.

On a regular hybrid electric vehicle functioning range, the battery should be about 10% state of charge to either side of this nominal chosen level, however exceptionally large current spikes could possibly lead it beyond this in both directions. This event depends upon the chemistry employed for the battery and its size, which will be determined by whether the vehicle design is “fast response” (power-assist or FR) or “slow response” (pseudo-EV or SR). The regenerative braking current spikes are likely to be of short duration and will be dependent on the braking pattern of the driver. On the other hand discharge periods will usually be longer, because they act for acceleration and/or hill climbing events in the duty cycle. Once more, the frequency and the intensity of the events will depend upon the driver’s attitude. Moreover there are periods of time, which can be possibly long, when the battery is functioning at very low levels or even not at all. During that the primary energy source (heat engine) is supplying everything required and the vehicle can be cruising or idling. Furthermore, in some configurations the vehicle does not idle in stalled traffic or lights but instead it shuts off and when required it starts again, and as such the battery is required to handle the frequent restarts [16]. Fig. 15 shows the average working range of the battery of a hybrid electric vehicle.



**Figure 13** HEV battery operating range.

One of the most important parts for battery operation is the vehicle control system. The vehicle control system must be capable to monitor the state of charge of the battery closely and then to adjust it when it is getting too close to either the top or bottom limit. If the vehicle undergoes excessive periods of acceleration or it must climb more than on hills, the battery can be drained to a low state of charge. In this case the primary power source energy can be used to charge the battery back up to an acceptable state of charge level. In a different case, frequent braking events can lead the battery to a high state of charge, making necessary the removal of some energy from the battery which can be used for vehicle operation or funneled into an external device or source. In order for the control system to be able to perform these actions, it must obtain a fairly accurate indication of the battery state of charge, probably within ~5%. This is one of the most difficult and important issues in the operation of a hybrid electric vehicle battery.

## 2.2 Drivetrain Architecture

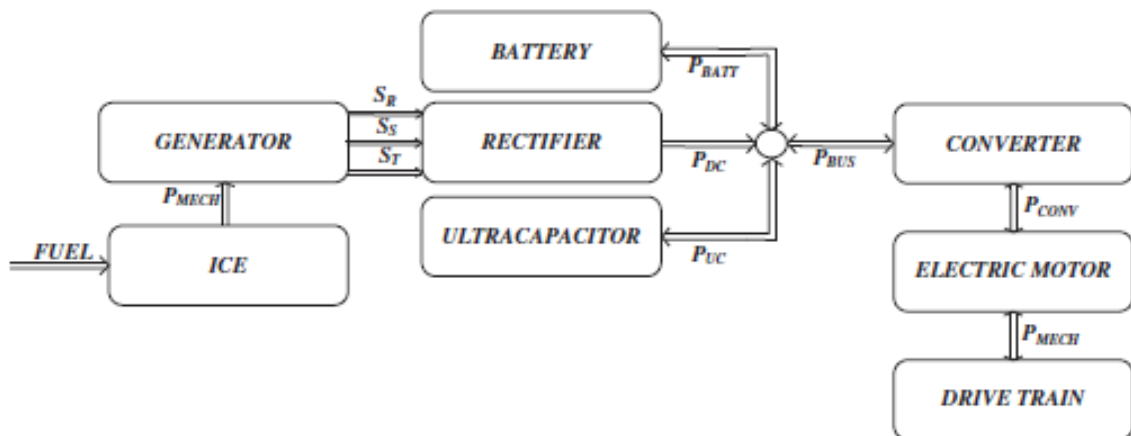
A significant element of a hybrid electric vehicle that differs from conventional fossil powered cars is the drivetrain. The drivetrain of every component of the powertrain that transmits power from the primary and secondary energy sources to the wheels of the vehicle. As such the architecture includes the transmission, the motor/generator, the internal combustion engine and final drive.

The primary concern with the design for hybrid electric vehicles is managing the energy transfer from the source to the load while minimizing the loss of energy for different driving cycles. As a fact hybrid electric vehicles have more electrical equipment such as electric machines, power electronics, embedded powertrain controllers, electronic continuously variable transmissions, energy converters and advanced energy storage devices in comparison to conventional internal combustion engine vehicles (ICEVs).

There are three main configurations for the drivetrain: Series, Parallel and Power-split.

### 2.2.1 Series hybrid electric vehicles

Series hybrid electric vehicles contain an internal combustion engine(ICE), a generator, battery packs, rectifier, capacitor (or flywheel), converter and electric motor. In this configuration there is no mechanical connection between the internal combustion engine and the wheels. The arrangement can be seen in fig. 14 [17].



**Figure 14** SHEV powerflow.

When the vehicle is in all electric mode the internal combustion engine is not working and the battery packs feed the system. The regenerative braking and the down slope driving provide a significant amount of energy. The ultracapacitors are used to extend the lifetime and the efficiency of the battery. When the battery reaches a low threshold the internal combustion engine is engaged. During country driving also the internal combustion engine is engaged. There are two possibilities of powerflow. In the event that the power demand of the electric motor is lower than the output power of the generator then the additional energy is provided to charge the batteries and the ultracapacitors. In contrast if the power demand of the motor is higher than the output of the generator then the additional required energy is provided by the ultracapacitor banks and the battery pack. The use of a motor to drive the wheel directly cancels the need for the conventional mechanical transmission elements such as gearbox, transmission shafts and differential and sometimes it is possible to eliminate the need for flexible couplings.

Consequently, the internal combustion engine can operate at its maximum efficiency point and hence the fuel efficiency improves and the carbon emissions are less than other vehicle configurations. Thus the series hybrid electric vehicle configuration has the advantage of being an optimized efficient power plant. Also there are possibilities for modularity. Other advantages include the optimized traction drive line, the internal combustion engine downsizing, the long operational life, the possibility of zero emission operation, the excellent transient response and the maturity of this well proven technology. The disadvantages are that it requires a larger traction drive system, careful design algorithms and the multiple energy conversions. Series hybrid configuration is mostly used in heavy vehicles, military vehicles and buses [18]. Benefits of the series hybrid configuration are summarized in Table 4 [19] and an actual example of a SHEV is shown in fig. 15.



**Table 4** Benefits of series hybrid configuration.

<b>Features</b>	Optimized efficient power plant Modular power plant possibilities Optimized efficient traction drive line Engine down sizing Space packaging advantages	Fast “black box” service exchange possible Long operational life Mature well proven technology Excellent transient response Zero emission operation possible
<b>Disadvantages</b>	Larger traction drive system Careful design algorithms a prerequisite Multiple energy conversions	
<b>Vehicle systems/ applications</b>	TEMSA Avenue Hybrid Orion VII Wrightbus electrocity	Tesla ultra light rail Conventional light rail New Tesla buses

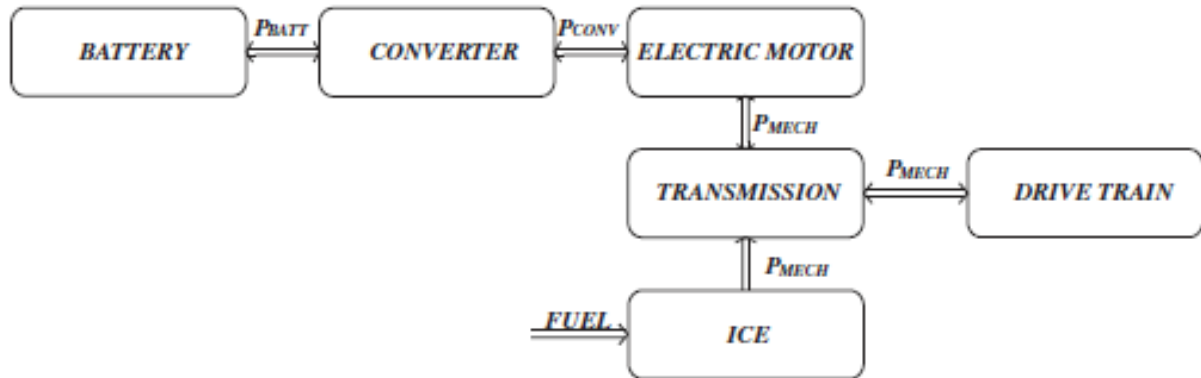


**Figure 15** Honda Civic Hybrid is a series HEV.

### 2.2.2 Parallel hybrid electric vehicles

In parallel hybrid electric vehicles the mechanical power output and the electric power output are both connected to the transmission. The components are battery, converter, electric motor, transmission and the internal combustion en-

gine. There are many control strategies used for the parallel configuration. The most common strategy is to keep the internal combustion engine always in on mode and operate at almost constant power output at maximum efficiency point. The configuration is shown in Figure 16 [17].



**Figure 16** PHEV powerflow.

In this configuration if the power required by the transmission is higher than the output power of the internal combustion engine, then the electric motor is turned on and as such power is supplied to the transmission by both the internal combustion engine and the electric motor. In contrast, when the power required by the transmission is lower than the output of the internal combustion engine, the electric motor operates as a generator and uses the remaining power to charge the battery packs. Also in this configuration, the regenerative braking power during downhill driving is utilized to charge the battery pack.

Some of the features of this configuration are the economic gain at a high cost, the option of a retarder but at complexity risk and the possibility of zero emission operation. The disadvantages are that it is an expensive system with a control complexity, careful design algorithms are a prerequisite, high voltages are needed for efficiency and the complex space packaging. The parallel configuration is implemented in the Honda Insight model, the Ford Escape SUV and the Lexus Hybrid SUV. Benefits of the parallel hybrid configuration are given in Table 5 [19] and an actual example of a PHEV car is presented in fig. 17.

**Table 5** Benefits of the parallel hybrid configurations.

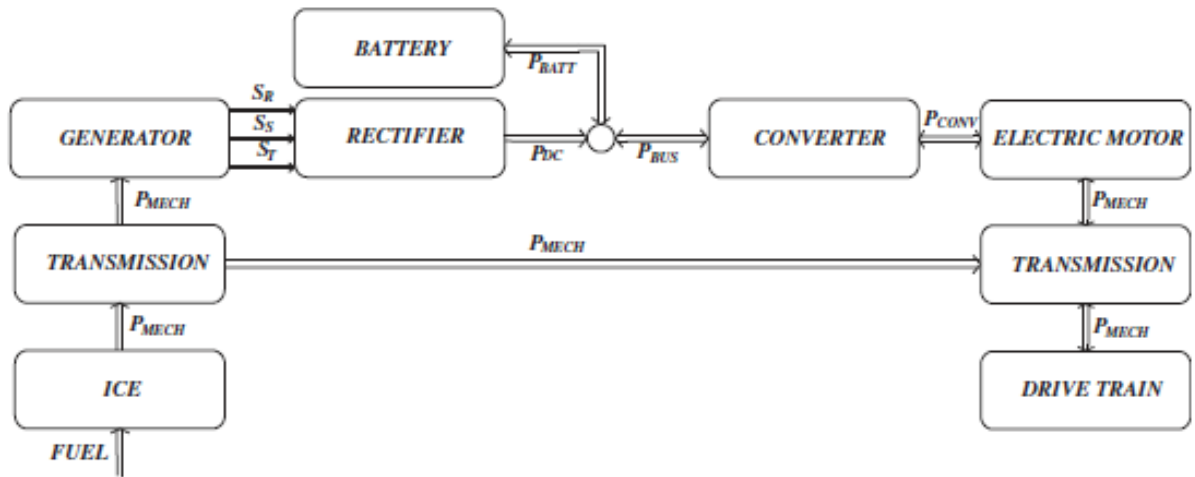
<b>Features</b>	Economic gain at high cost Retarder option but at complexity risk Zero emission operation possible
<b>Disadvantages</b>	Expensive system Control complexity Careful design algorithms a prerequisite High voltages needed for efficiency Complex space packaging
<b>Vehicle systems/ applications</b>	Hino HIMR Bus/Heavy truck market



**Figure 17** Honda Insight is a parallel HEV.

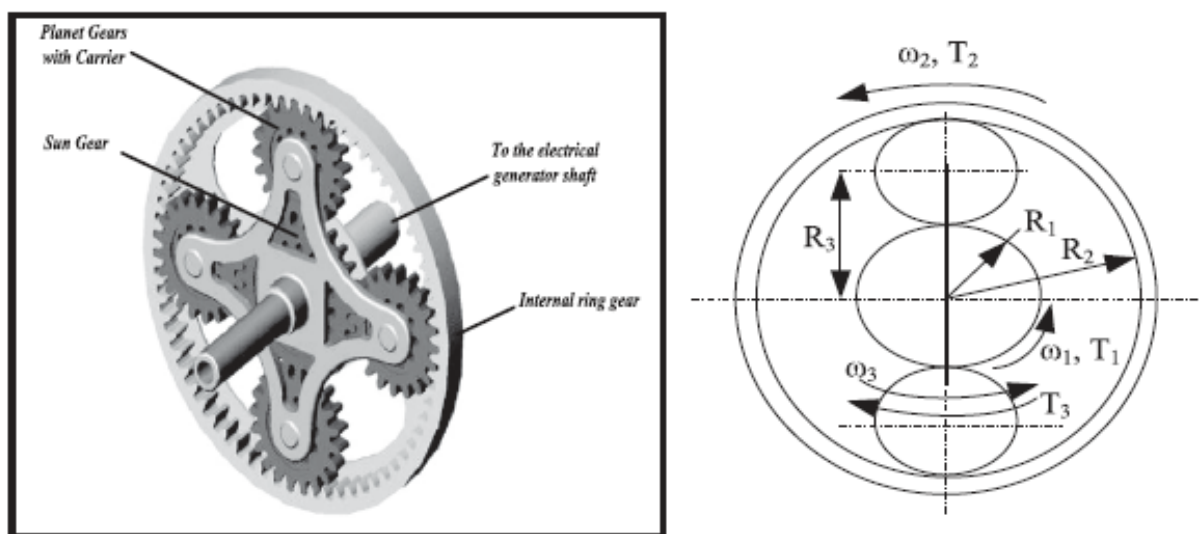
### 2.2.3 Power-split hybrid electric vehicles

The combination of parallel and series hybrid configurations into a single package is the power-split configuration. The series-parallel or power-split hybrid powertrain combines the series hybrid system with the parallel hybrid system to achieve the maximum advantages of both systems. It is neither fully parallel nor series configuration. The fundamental combination architecture is shown in Figure 18 [16].



**Figure 18** Power-split powerflow

In this setup mechanical energy passes through the power-split in two series and parallel paths. In the series path, the internal combustion engine drives the generator which produces electrical energy to run the electric motor to drive the car. In the parallel path there is no energy conversion and the mechanical energy output of the engine is directly transferred to the final drive via the power split device, which is a planetary gear system [20]. An example of a planetary gear is shown in Figure 19. Depending on the connection to the sun, planet and outer ring gears, the speed of the vehicle can be adjusted.  $T_1$ ,  $T_2$ ,  $T_3$  are the torques,  $\omega_1$ ,  $\omega_2$ ,  $\omega_3$  are the rotational speeds of the gear and  $R_1$ ,  $R_2$ ,  $R_3$  are the radii of the gear[21][22].



**Figure 19** View of planetary gear system.

$$\omega_3 = \frac{R_1}{2R_3} \omega_1 + \frac{R_2}{2R_3} \omega_2$$

$$T_3 = \frac{2R_3}{R_1} T_1 = \frac{2R_3}{R_2} T_2$$

An all electric drive is possible in this configuration. There are many possible control strategies with this configuration and each manufacturer has its own. However these strategies are a combination of the ones mentioned above in the two previous configurations. The internal combustion engine's torque output at lower RPMs is minimal, so in conventional vehicles a larger engine is required for acceleration from standstill. This fact, however, means that the engine has more power than needed for steady speed cruising. On the other hand, an electric motor exhibits maximum torque at any speed, and so standstill, and is appropriate to supplement the engine's torque shortage at low RPMs. Features for power-split HEVs are shown in Table 6. This Configuration is used most commonly in passenger cars with the examples of Toyota Prius (fig. 20) and the Chevrolet Volt.

**Table 6** Features for power-split HEV configurations.

Features	Zero emission operation possible
<b>Disadvantages</b>	Very expensive system Control complexity Careful design algorithms a prerequisite Complex space packaging Outdated by coupled hybrid topology
<b>Vehicle systems/ applications</b>	Fiat experimented Nissan Experimented





**Figure 20** Toyota Prius is power-split HEV.

#### **2.2.4 Choice of the appropriate architecture and other requirements**

With all three possible configurations the manufacturer must consider and choose which architecture is best for the vehicle in consideration.

For hybrid electric vehicles with a demand for high all electric range, both parallel and series type drivetrain architectures can be successful. In both cases, the sole source for driving the wheels is the traction motor and so it must be sizeable enough to supply the necessary speed and torque for the propulsion of the vehicle all the way through the entire speed range. Power-split architectures with epicyclical gears may be challenging because the speed ratios between the motors, the engine and the wheels are inflexible in relation to one another.

The operation of the engine of a hybrid electric vehicle is discontinuous; as a result it places additional requirements to the drivetrain and its parts. As an example, in parallel hybrid electric vehicles, the electric motor must be able for multiple operation modes in order to participate in the different driving cycles. Other than providing torque for the driving of the vehicle, it has to be able to provide torque for stopping and starting the internal combustion engine, some-

thing that may happen occasionally during the operation of the vehicle. In series and power-split architectures the traction motor is not required to be multifunctional like in parallel drivetrains, however the generator may be required to have different operational modes depending on the operation of the hybrid electric vehicle.

Although hybrid electric vehicle architecture has better efficiency and lower emissions in comparison to conventional vehicles, their environmental impacts vary. Series type vehicles have greater losses because of the increased number of energy conversion in their system, something that leads to a generally lower efficiency than an analogous parallel or power-split system. On the other hand hybrid electric vehicles with series drivetrains have the benefit of being capable to operate their internal combustion engine in the optimum spectrum continuously which has the outcome of lower emissions. The parallel and power-split drivetrain architectures have the advantage of reduced engine sizing and enlarged electrochemical capacity, however they require their engines to operate over a wider range, which is not idyllic for emissions. The previous argument although affects both architectures the power-split type has better control on the range of operation of their internal combustion engine because the engine is not directly connected to the drive wheels like parallel hybrid electric vehicles.

The main attributes of the drivetrain architecture decisions that shape the vehicle-level characteristics of the hybrid electric vehicles are packaging and cost constraints. The price of electric motors, power electronics and batteries escalates with growing torque output, and consequently leads the hybrid electric vehicles designer toward smaller electronic machinery with more complicated mechanical connections. One must not neglect that the under sizing of these components leads to decreased vehicle mass and consequently to improvements on the hybrid electric vehicle's fuel economy and performance. Generally series hybrid electric vehicles call for larger electronic components including both motor and generator which results to a heavier and more expensive drivetrain system. Parallel hybrid electric vehicles require less power electronic components, which has a result of a drivetrain that is more compact, lighter and more economical than the ones of series hybrid electric vehicles.

The fact that there are more electrical connections instead rather than mechanical connections, component placement and orientation is the least restricted in series hybrid electric vehicles. Series powertrains are most suited to medium and heavy duty hybrid electric vehicles because of the extra area that is on hand for the components and the vehicle platform's increased forbearance for vehicle weight. This types of systems also display their greatest efficiency gains at low speed, urban type driving.

Depending on the design goals for the overall vehicle, the various architectures fulfill aspects unequally. When environmental impact and simplicity are the primary goals with less emphasis on performance, range and cost, the series architecture may be optimal. When drivability and performance are crucial and more assets are available to cover design complexity and controls, the power-split architecture may be best possible. In conclusion, when environmental impact and cost are the foremost design criteria then parallel drivetrains may be most favorable. Table 7 summarizes the advantages and disadvantages of the three configurations.

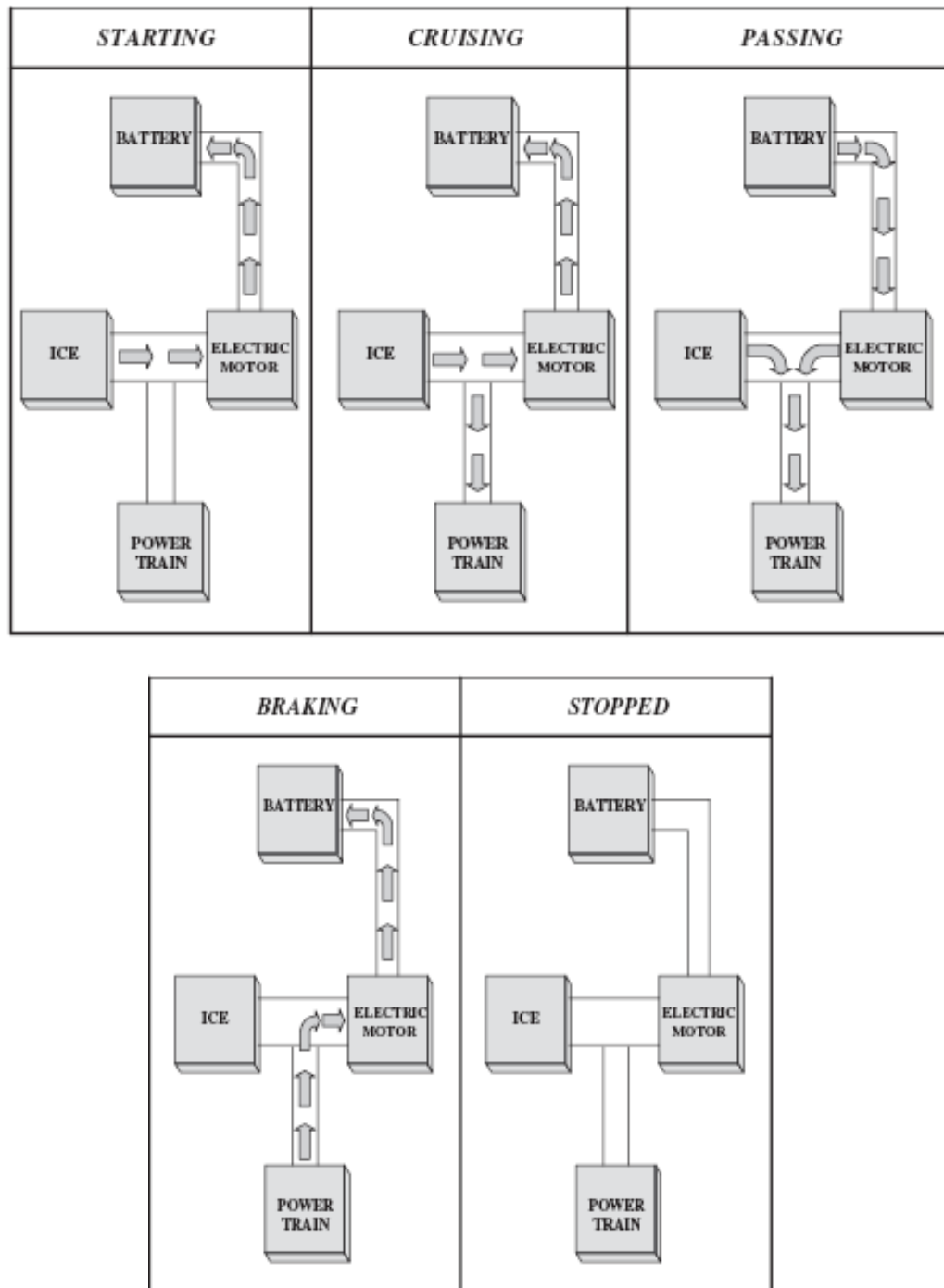


**Table 7** Comparison of vehicle architecture

Battery system	Series	Parallel	Power-split
Weight	0	+	-
Cost	0	+	-
Controls	+	0	-
Number of components	0	+	-
Volume	-	+	-
Performance	-	+	+
Drivability	0	0	+
Efficiency	-	+	+
Design freedom	-	0	+

## 2.3 Energy Management

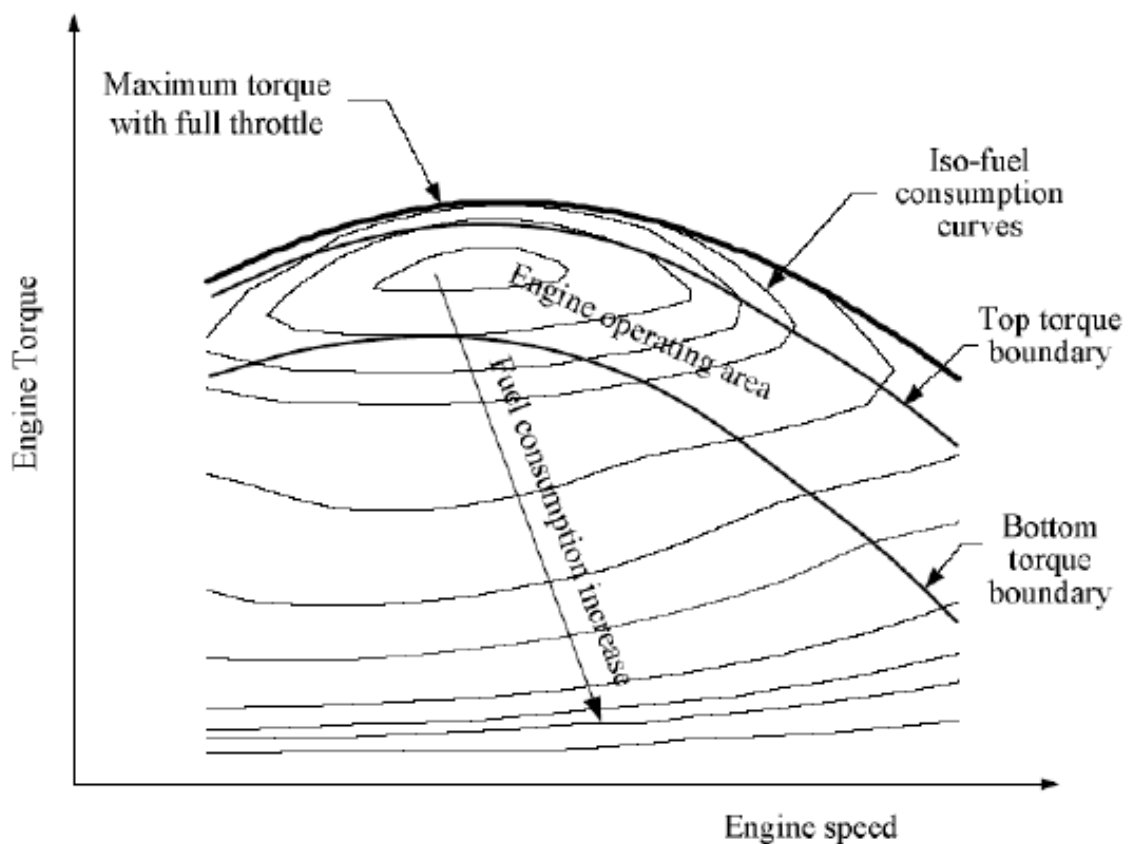
In a conventional hybrid electric vehicle, the aim of power strategy is to maintain the battery state of charge in an adequate range with consideration for the battery health. However, the grid charged battery of plug-in hybrid electric vehicles presents the option of taking advantage of electricity and fuel energy simultaneously in which usage of electric energy stored in battery packs is preferable. In order to take advantage of the plug-in hybrid electric vehicle powertrain, appropriate power flow energy must be applied. The controller resolves operating points for each component and conveys the sufficient commands to the local controller of each subsystem. In fig 21 some basic operating modes of a hybrid electric vehicle are presented.



**Figure 21** The basic operation modes of a hybrid electric vehicle.

The first option for the power management of the plug-in hybrid electric vehicle is to operate the vehicle on pure electric mode until the point when all energy stored in the battery is depleted, which is the definition of all-electric range (AER) [22]. Afterwards, the vehicle operates as a conventional hybrid electric vehicle in charge sustained mode to steady the state of charge. In the case that the distance traveled between the recharging is less than the defined

plug-in hybrid electric vehicles at electric range, the most effective mode of operation is just electric mode which does not spend a single drop of petrol. However, in realistic conditions, many commutes are greater distance wise and sometimes the demand for power is greater than what the battery is capable of providing which leads to inevitable engine operation. Some surveys [23],[24] have shown that charge depletion (CD) strategy, operating both battery and engine on the same time, could be more efficient in comparison with simple all electric range followed by sustained charge control strategies if the journey is longer than the all electric range.



**Figure 22** Operation area of engine [24]

Gao et al. [23] has suggested two different electric vehicle/charge sustained (EV/CS) and blended control strategies or parallel configuration. They have suggested a manual shifting option between electric vehicle and charge sustained for the driver. In electric vehicle (EV), the vehicle facilitates the stored energy in the battery aggressively and in charge sustained (CS), the state of charge of the battery is sustained around a specific value. In blended control

strategy or charge depletion mode, both engine and electric motor function simultaneously. With this strategy, the engine is always operated in its efficient region as illustrated in figure 22. The engine is controlled as no excess energy remains to charge the battery to prevent charging and discharging waste. When the torque required is higher than the top torque boundary, the engine is managed to operate on this boundary so that the remaining power demand to be covered by the electric motor. When the required torque is between the boundaries, the engine propels the wheel exclusively. On the opposite, when the torque needed is below the bottom boundary, the engine is shut off and the vehicle operates in pure electric mode.

In [24], four different strategies were simulated and compared for a power-split plug-in hybrid electric vehicle with 16 km all electric range battery pack in Palm Springs Aerial Tramway for a vehicle with similar performances with Freyermuth et al. model in [25]:

1. Electric Vehicle / Charge Sustaining (EV/CS)
2. Differential Engine Power
3. Optimal Engine Power
4. Full Engine Power

In Electric Vehicle / Charge Sustaining mode, the engine is operating only when the power demanded is greater than the power provided by the battery [22]. Differential Engine Power is similar to Electric Vehicle / Charge Sustaining but the engine turns on at a lower than maximum power level of the electrical system. Optimal Engine Power strategy pursues to propel the engine operation close to peak efficiency. The engine start threshold can be derived from simulation for various predetermined journey distances. In other words, for longer journeys to continue more in charge depletion before starting charge sustain, the threshold must be reduced. In the Full Engine Power setting, if the engine turns on it will provide all the power demand of the vehicle for the drive cycle and no power will be drawn from the battery. The target of this strategy is to press the engine to function in higher power demand and as such in higher efficiency. The concept of increasing efficiency in charge depletion is to push the engine to function and ignite in higher average efficiencies during the journey as

much as possible by saving electric energy for low demand energy parts of drive cycles. The simulation resulted in Differential Engine Power strategy which has similar overall efficiency with Electric Vehicle / Charge Sustaining because the engine operation in low loads decreases the overall efficiency. Full Engine Power strategy had the greatest result with almost 9% improvement for an engine ignite threshold designed for 32 km journey even more than Optimal Engine Power strategy. Even though the engine functions more efficiently in Optimal Engine Power strategy, the general efficiency is reduced because of the wastes in battery charging by the excess energy supplied in optimum engine operation point and consequence of more power recirculation in power split. The fascinating result was that the Optimum Engine Power strategy had no significant improvement over Electric Vehicle / Charge Sustaining and sometimes worsened the efficiency for some trip distances [25].

Moura et al [26] suggested a stochastic optimal approach for power management, to optimize a power-split drivetrain for a probabilistic distribution of many drive cycles, instead of a single one. By means of a discrete time Markov chain, the model of drive cycle has been predicted. The fuel and electricity costs are both considered in a defined cost function. Accordingly, the advantages of controlled charge depletion over charge depletion have been explored. The simulation showed 6.4% and 8.2% less total cost of energy and fuel consumption respectively for this blended strategy in comparison to normal charge depletion strategy. The blended and normal charge depletion had alike cost for the duration of depletion phase, but the advantage of blended strategy arises from its delay entry into charge sustaining mode.

The information of travel distance could alter the way stockpiled electric energy in battery is used to optimize fuel consumption. Gao et al.[ref 6 apo a study] suggested a manual shifting mode between Electric Vehicle / Charge Depletion modess to somehow affect the knowledge of future drive cycle. Considering the journey distance, Share et al. [24] have chosen different engine ignition thresholds for different journey distances and deduced that the basic information on trip distance can decrease fuel consumption. Moura et al. [26] attempted to increase fuel efficiency in blended strategy based on a cost function which led to a delayed start of charge sustaining mode. Gong et al. [27],[28]

proposed that it is possible to improve the control strategy if a plug-in hybrid electric vehicle if the trip information is determined a priori by means of recent advancement in intelligent transportation system (ITS) based on the usage of global positioning system (GPS) and geographical information system (GIS). In [27],[28], a dynamic programming (DP) approach has been used to drive the battery to be depleted at the end of the journey. Dynamic programming approach provides a global optimal solution, nevertheless the dynamic programming is considered as not an applicable technique especially for real time applications because it has a long computational procedure. The global optimization by the process of dynamic programming algorithm offered a significant 44.9% efficiency improvement [28] in comparison with Electric Vehicle / Charge Sustaining control approach.

## **2.4 Charging Profile**

A fundamental characteristic of plug-in hybrid electric vehicles is their ability to recharge their energy storage system from the electric grid. The charging system is the set of controls, communication, power electronics, and power transfer equipment that makes the recharging of plug-in hybrid electric vehicles possible. The design of charging systems for plug-in hybrid electric vehicles consists of both the specification of the physical hardware for charging and the specification of the control system which controls the charging strategy for the vehicle.

### **2.4.1 State of the art for ESS charging systems**

Plug-in hybrid electric vehicle energy storage systems charging can be constrained or unconstrained. Unconstrained charging is the simplest form of plug-in hybrid electric vehicle charging and allows the plug-in hybrid electric vehicle owner to plug in at any time of the day without any limitations. Constrained charging is defined as any charging strategy in which the electric utility and vehicle are able to cooperatively implement charging strategies. These constrained charging strategies will aim to limit plug-in hybrid electric vehicle charging loads so that they are not coincident with the peak loads of the day. The first generation of plug-in hybrid electric vehicles will use unconstrained opportunity

charging due to the initial low volume of vehicles and low impact on the electric grid. However, most research to date has shown that as plug-in hybrid electric vehicles penetrate the market, unconstrained charging will need to be replaced with some level of constrained charging to reduce the possibility of exacerbating peak electric demands. Constrained charging behavior can potentially permit up to 50% plug-in hybrid electric vehicle market penetration without an increase in generation capacity and also presents the possibility for the electric utility to regulate the system more effectively resulting in more uniform daily load profiles and reduced operational costs. Due to the long-term risks involved in allowing unconstrained charging to occur, this section will only focus on how controlled charging impacts the design of plug-in hybrid electric vehicles. The most prevalent strategies currently being pursued to implement constrained charging are labeled as valley filling, demand response, vehicle-to-grid (V2G), real-time price charging, and delayed charging.

The SAE J1772 standard has been developed to provide design guidance for plug-in hybrid electric vehicle power transfer connections. The standard requires plug-in hybrid electric vehicle power transfer connections to be able to operate on single phase 120V or 240V and also support communication. The power transfer equipment can either be a separate component or be integrated into the windings and power electronics of the traction motor and motor drive. In order for plug-in hybrid electric vehicles to be capable of vehicle-to-grid, either an inverter must be added to the plug-in hybrid electric vehicle's power electronics or equipment capable of utilizing the on-board charger as both an inverter and a rectifier would need to be used. Although various power levels of charging have been proposed, level 1 charging (110 V, 15 A) is most common. Level 2 and level 3 quick chargers have increased power ratings, but the installation of level 2 and level 3 chargers can be a slow and costly process, especially for residential installations. In fig. 23 the Yazaki's SAE J1772 compliant electric vehicle connector is displayed.



**Figure 23** Yazaki's SAE J1772 compliant electric vehicle connector.

All of the constrained charging strategies require some level of communication between the plug-in hybrid electric vehicle or plug-in hybrid electric vehicle owner and the electric utility or grid system operator. For demand response, real-time pricing, and delayed charging, the plug-in hybrid electric vehicle or plug-in hybrid electric vehicle owner must be able to receive and process pricing and/or power interrupt signals sent by the electric utility. The remaining charging strategies, valley filling and vehicle-to-grid charging, require electronic two-way communication between the plug-in hybrid electric vehicle and the electric utility or the grid system operator. Two-way communication is required because the electric utility or the grid system operator needs to know the state of charge of all the plug-in hybrid electric vehicles connected in order to forecast the expected charging load for the valley-filling algorithm and the availability of plug-in hybrid electric vehicles for providing vehicle-to-grid frequency control. Research has shown that the communication task can be achieved by integrating Broadband over Powerline and HomePlug™, Zigbee™, or cellular communication technologies into a stationary charger or into the plug-in hybrid electric vehicle's power electronics.



#### **2.4.2 Requirements of the energy storage systems charging system design based on plug-in hybrid electric vehicle vehicle-level attributes**

Vehicle-level attributes such as fuel economy and all electric range transmit design requirements to plug-in hybrid electric vehicle energy storage system charging systems. These vehicle-level attributes impact the decision of what power rating is most appropriate for plug-in hybrid electric vehicle power transfer equipment. For example, if the design of a plug-in hybrid electric vehicle is aimed at increasing the vehicle's all electric range, the plug-in hybrid electric vehicle's energy storage system will need to be augmented to store more energy. This increased capacity of the energy storage system will require longer charging times, which can be reduced through the utilization of level 2 or level 3 power transfer equipment. However, power transfer equipment with higher power ratings increases the cost and complexity of the energy storage system charging system.

#### **2.4.3 Constraints on vehicle-level design based on energy storage system charging characteristic attributes**

Studies have stated that constrained charging can provide the electric utility an opportunity to improve resource utilization. As a result of this, the electric utilities will be able to provide reduced rates to plug-in hybrid electric vehicle owners who comply with the regulations of the constrained charging program. These reduced rates help improve vehicle performance in terms of operating cost. However, constrained charging programs can lead to reductions in fuel economy and all electric range since the permitted charging time or time with reduced electric charging rates would be limited and decrease the number of hours which plug-in hybrid electric vehicles are able to charge each day. As the allowable charging hours are decreased, the ability of a plug-in hybrid electric vehicle to fully recharge begins to decline. Plug-in hybrid electric vehicles utilizing level 1 charging can be significantly impacted since it take approximately 8 hours to charge a vehicle with an energy storage system usable capacity similar to a Chevrolet Volt. If a plug-in hybrid electric vehicle is incapable of fully recharging the energy storage system, the all electric range/effective all electric range of the vehicle will be reduced and could decrease the fuel economy of the vehicle if the plug-in hybrid electric vehicle is forced to operate in charge sus-

taining mode more frequently. Increased operation in charge sustaining mode reduces plug-in hybrid electric vehicle performance in terms of fuel economy, which is one of the major vehicle attributes being considered to justify the higher cost of plug-in hybrid electric vehicles in comparison to conventional vehicles and hybrid electric vehicles.

#### **2.4.4 Constraints on system-level design based on energy storage system charging characteristic attributes**

Regardless of the type of constrained charging strategy utilized, the energy storage system charging components and strategies will impose constraints on the electric grid. The largest impact controlled charging will have on the electric grid is associated with the communication requirements needed between plug-in hybrid electric vehicles and plug-in hybrid electric vehicle owners and the electric utility or grid system operator. The simplest way in terms of communication that an electric utility can control charging behaviors is with time of use (TOU) rates. Time of use rates can be relayed to plug-in hybrid electric vehicle owners through rate plans that only change based on time of day and year and require the installation of an electric meter capable of metering energy transfer in real time for billing purposes. However, it is yet to be determined if time of use rates are strong enough motivators to affect the charging habits of the majority of plug-in hybrid electric vehicle owners. The next level of complexity available for the electric utility is the use of real-time data communication. One of the problems associated with using real-time data transfer to centrally monitor and control a large number of plug-in hybrid electric vehicles is that it has been seen as an overwhelming task. Constrained charging of plug-in hybrid electric vehicles will require a large investment in electric grid infrastructure and will significantly increase the workload of the electric utility.

Another large concern currently being expressed by electric utilities is the expected increased loads on residential transformers and other electric grid components. Studies have shown that the acceptance of hybrid electric vehicles has typically occurred nonuniformly throughout a geographic area, and they are expecting the adoption of plug-in hybrid electric vehicles to follow a similar pattern. This poses a problem for the utilities especially with respect to the loading of residential transformers because most residential transformers are already

approaching their recommended use capacities. Another concern is that although constrained charging of plug-in hybrid electric vehicles will help the electric utility keep from exacerbating their peak demands, constrained charging may force transformers especially in residential areas and other grid infrastructure to be fully utilized for the majority of the day. This increased use would reduce the amount of rest and cooling time the equipment would experience which could shorten the operational life of the transformers and other electric grid equipment.

### **3 Presentation of models**

In this dissertation three commercial models were chosen to be compared in the following chapter. In this chapter the three models are presented. The models are Chevrolet Volt, Nissan Leaf and Toyota Prius. The first two models were released this year so accumulation of technical data was difficult. However since these two vehicles represent cutting edge technology in the sector of electric automotive they were chosen to be investigated.

### 3.1 Chevrolet Volt



**Figure 24** Chevrolet Volt.

The Chevrolet Volt is a plug-in hybrid electric vehicle manufactured by General Motors. The Volt has been on sale in the U.S. market since mid-December 2010, and is the most fuel-efficient compact car sold in the United States, as rated by the United States Environmental Protection Agency (EPA). According to General Motors the Volt can travel 25 to 50 miles (40 to 80 km) on its lithium-ion battery alone. The EPA official all-electric range is 35 miles (56 km), and the total range is 379 miles (610 km). The EPA rated the Volt's combined city/highway fuel economy at 93 miles per gallon gasoline equivalent (MPG-e) in all-electric mode, and at 37 mpg-US (6.4 L/100 km; 44 mpg-imp) in gasoline-only mode, for an overall combined gas-electric fuel economy rating of 60 mpg-US (3.9 L/100 km; 72 mpg-imp) equivalent (MPG-e). In the Eurozone the Volt platform will be sold as the Opel/Vauxhall Ampera.

Among other awards and recognition, the Chevrolet Volt won the 2009 Green Car Vision Award, 2011 Motor Trend Car of the Year, 2011 Green Car of the Year, 2011 North American Car of the Year, and 2011 World Green Car.

The Society of Automotive Engineers' (SAE) definition of a hybrid vehicle states that the vehicle shall have "two or more energy storage systems both of which must provide propulsion power, either together or independently." General Motors has avoided the use of the term "hybrid" when describing its Voltec

designs, even after the carmaker revealed that in some cases the combustion engine provided some assist at high speeds or to improve performance. Instead General Motors describes the Volt as an electric vehicle equipped with a "range extending" gasoline powered internal combustion engine (ICE) as a genset and therefore dubbed the Volt an "Extended Range Electric Vehicle" or E-REV. In a January 2011 interview, the Chevy Volt's Global Chief Engineer, Pamela Fletcher, referred to the Volt as "an electric car with extended range". According to SAE's definition the Volt is a hybrid vehicle, due to the combination of an internal combustion engine and electric motors, and its configuration can be referred to as a plug-in hybrid. Although the configuration of a battery electric vehicle with range extender was described above, this model has a slightly different configuration because in some cases the internal combustion engine can provide torque/mechanical energy to the wheel. More details are given later.

### **3.1.1 Specifications**

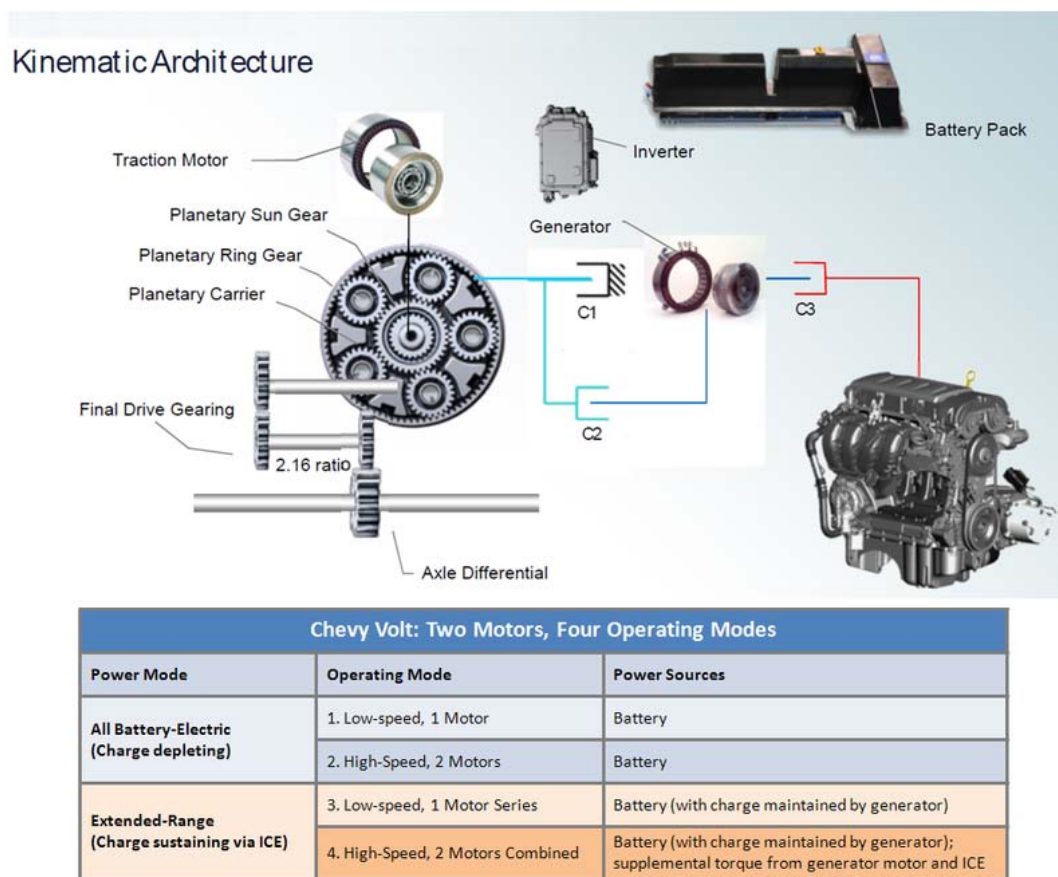
#### ***Drivetrain***

The 2011 Chevrolet Volt has a 16 kW·h (7 A·h) (10.4 kW·h usable) lithium-ion battery pack that can be charged by plugging the car into a 120-240 VAC residential electrical outlet using the provided SAE J1772-compliant charging cord. No external charging station is required. The Volt is propelled by an electric motor with a peak output of 111 kW (149 hp) delivering 273 lb·ft (368 N·m) of torque. After the Volt battery has dropped to a predetermined threshold from full charge, a small naturally aspirated 1.4-liter 4-cylinder internal combustion engine (Opel's Family 0) with approximately 80 horsepower, burns premium gasoline to power a 55 kW (74 hp) generator to extend the Volt's range or when performance needs to be improved, the gas engine engages mechanically to assist propulsion directly. The generator has the possibility of acting as an electric motor with a power of 63kW. The vehicle also has a regenerative braking system. The electrical power from the generator is sent primarily to the electric motor, with the excess going to the batteries, depending on the state of charge (SOC) of the battery pack and the power demanded at the wheels. The Volt requires premium gasoline because the higher octane rating fuel allows the 10.5:1 compression ratio engine to maximize its fuel efficiency by 5 to 10% as compared to regular gas.

The following information details on the operation modes of the Chevrolet Volt where provided by General Motors in the serial media launch events.

The Volt's drive unit uses an on-axis configuration; motors and gear-set are mounted in an in-line with the range-extending internal combustion engine. Two of the clutches are used to either lock the ring gear of the planetary gear-set or connect it to the generator/motor depending on the mode. The third clutch connects the internal combustion engine to the generator/motor to provide range extension capability.

The 111 kW traction motor is permanently connected to the sun gear, and the final drive (gear reduction, differential) is permanently connected to the planetary carriers. The planetary carrier gears are used to modulate gearing ratios between the vehicle's electric motors, its internal-combustion engine, and its 2:16 final drive. In fig. 25 the kinematic architecture is displayed [29].



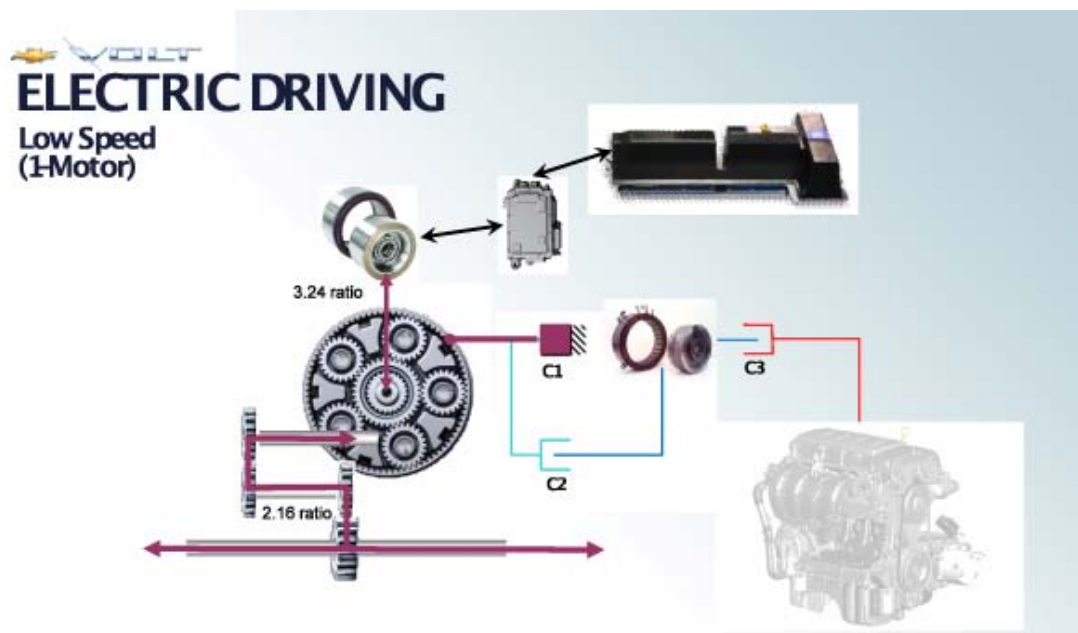
**Figure 25** Chevrolet Volt kinematic architecture.

The Volt has two primary driving modes:

- All battery-electric (charge depleting), in which the battery is the sole source of power for the motors; and
- Extended-range (charge sustaining), in which the battery and engine work together in different operating modes to power the traction motor and to improve overall efficiency.

Each of these two driving modes is supported by two drive unit operating modes: a low-speed, 1-motor mode, and a high-speed, 2-motor mode.

*Mode 1: Low-speed EV Propulsion (Engine Off).* In this mode, the ring gear is held (locked) by clutch C1. With clutch C2 and C3 disengaged, the generator-motor is decoupled from the engine as well as the planetary gearset. As the traction motor is permanently coupled to the sun gear, the planetary carriers must rotate when the traction motor rotates. Since the planetary carriers are permanently coupled to the final drive, the traction motor propels the vehicle. The generator-motor and the engine are idle during this mode, although the engine is free to start if necessary (example: engine maintenance mode). In fig. 26 a visual display of mode 1 is portrayed [29].

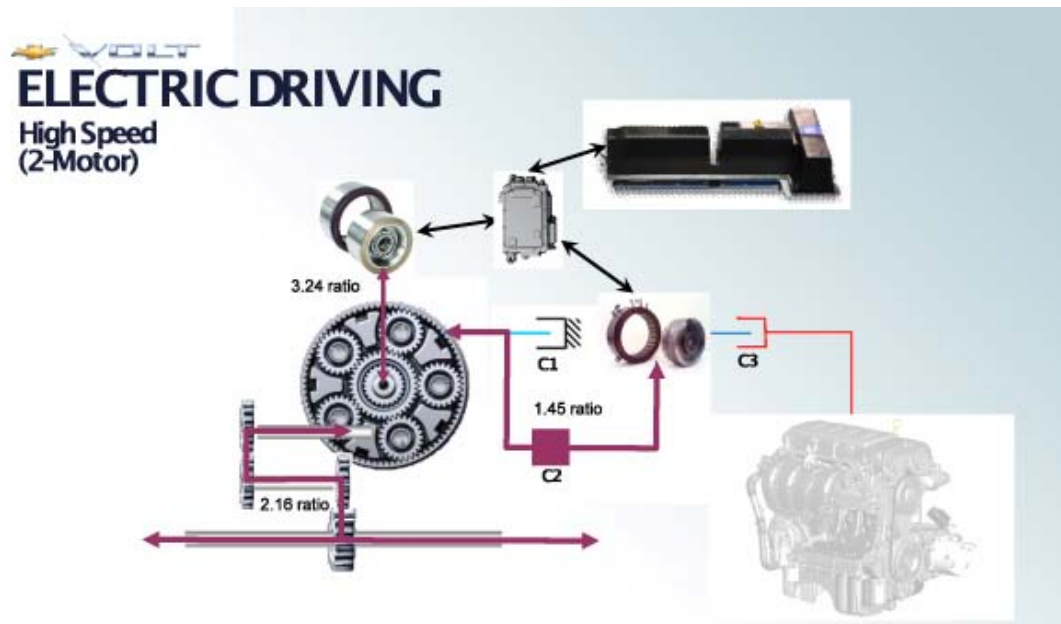


**Figure 26** Mode 1.

Virtually all of the vehicle's motive power is therefore delivered by the traction motor in this mode, including hard accelerations, using power supplied by the battery pack. With this configuration, the traction motor can produce up to 111 kW (149 hp) and deliver up to 370 N·m (273 ft·lb) of torque.



*Mode 2: High-Speed EV Propulsion (Engine Off).* As vehicle speed increases, motor speed and losses also increase. To engage both motors and preserve motor efficiency, clutch C1 is disengaged, allowing the ring gear to rotate. At the same time, clutch C2 is engaged, connecting the ring gear to the generator-motor. The generator-motor is then fed current from the inverter, and runs as a motor. The engine remains disengaged from the generator-motor. In fig. 27 a visual display of mode 2 is portrayed [29].



**Figure 27** Mode 2.

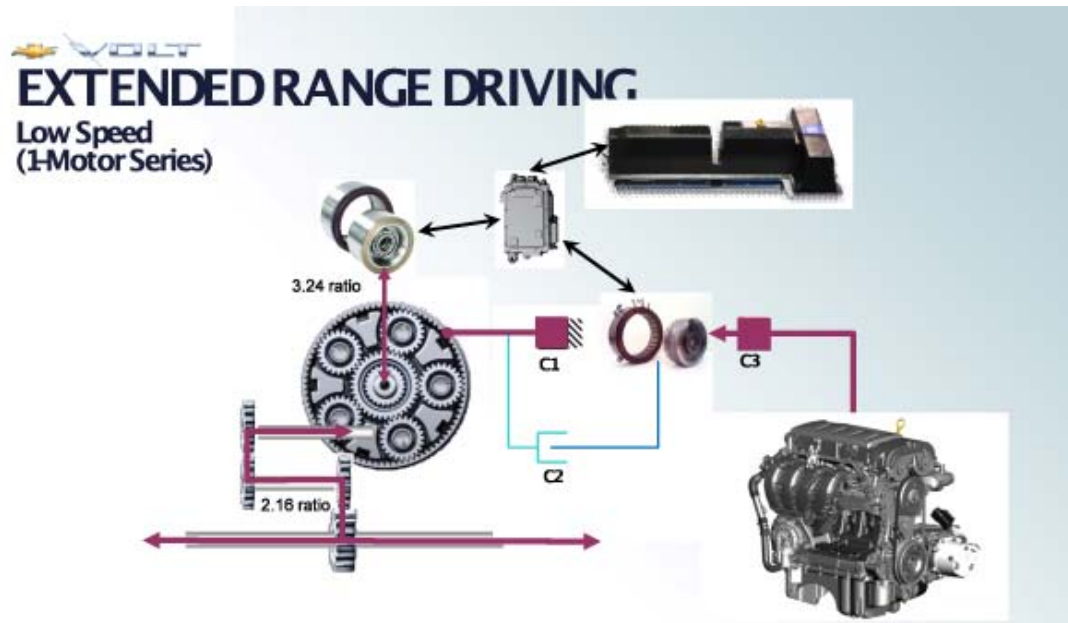
This mode allows the two electric machines to operate in tandem at a lower speed than if the traction motor alone was providing torque. The speed of the traction motor in this mode drops to about 3250 rpm from 6500 rpm in the 1 motor mode, according to Pam Fletcher, Global Chief Engineer for Volt and Plug-In Hybrid Electric Powertrains.

This strategy allows the Volt to wring out as much as two extra miles of all-electric operation out of its battery pack, depending on operating conditions. However, switching from low-speed to high-speed EV mode requires the simultaneous operation of two clutches.

*Mode 3: Low-speed Extended-Range Propulsion (Engine Running).* Once the Volt's battery pack has reached its minimum state of charge (SOC) (which varies depending on operating conditions), clutch C1 engages, locking the ring gear, and clutch C2 disengages, decoupling the generator-motor from the ring



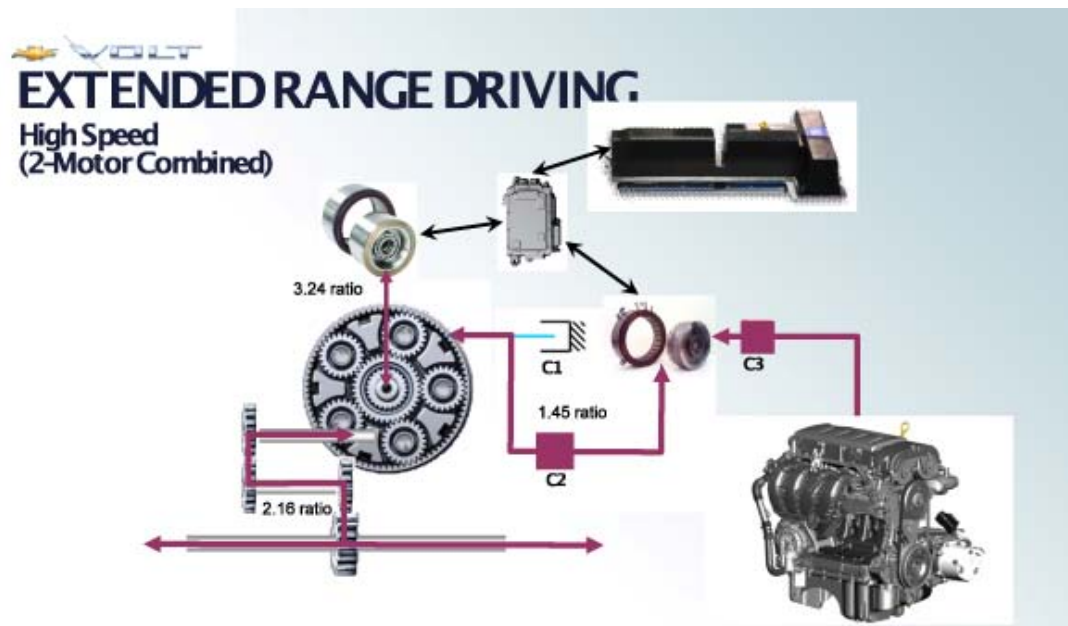
gear. At the same time, clutch C3 engages to couple the Volt's 1.4 liter Ecotec range-extending engine to the generator-motor, so that it may be operated in generator mode. In fig. 28 a visual display of mode 3 is portrayed [29].



**Figure 28** Mode 3.

During low speeds as well as hard accelerations, the traction motor propels the vehicle. The engine drives the generator-motor, and power to drive the traction motor is delivered by the generator-motor as well as the battery pack via the Volt's inverter. Under most conditions, the generator will provide enough power to maintain minimum battery SOC, and therefore allow the vehicle to remain in this mode until it is plugged in.

*Mode 4. High-Speed Extended-Range Propulsion (Engine Running).* The blended two-motor electric propulsion strategy used at higher speeds in EV driving has also been adapted for extended-range driving. In this mode, the clutches that connect the generator/motor to both the engine and the ring gear are engaged, combining the engine and both motors to drive the Volt via the planetary gear set. All of the propulsion energy is seamlessly blended by the planetary gear set and sent to the final drive. In fig. 29 a visual display of mode 4 is portrayed [29].



**Figure 29** Mode 4.

This novel mode—which GM calls “combined mode”—enables a 10-15% improvement in efficiency at steady state cruising speeds compared to a comparable single-motor mode, GM says. Under no circumstance can the Volt be propelled by engine torque alone; the traction motor must be operating if the vehicle is to move and the engine is to provide torque.

Pam Fletcher says, “When we’re in this combination...on this planetary gearset we are driving the engine-generator combination onto the ring gear. We are utilizing the traction motor to provide the reactionary force so that we can ultimately drive the output. That is what happens in combined mode, that’s what allows us to get the 10-15% more efficiency.”

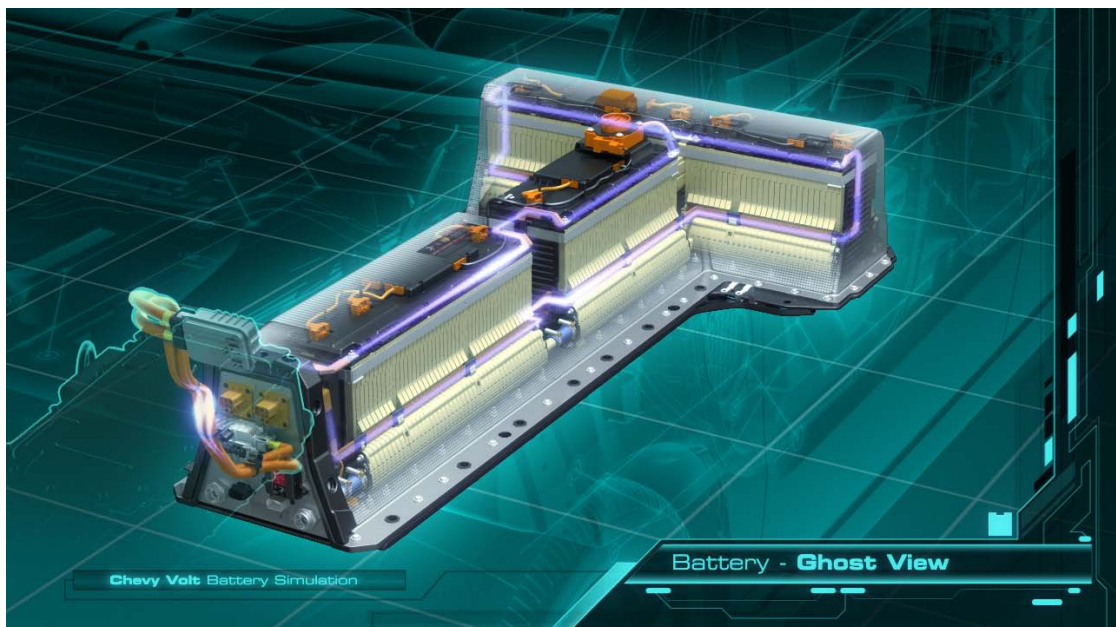
In this mode, the generator still continues to produce electricity as well as deliver torque via the gearset, Fletcher said. The ratio of torque to power generation varies with operating conditions, and is, as the rest of the system, under the management of the control software, according to her. As noted earlier, the control software and architecture enabling this drive unit is critical to its overall success.

The Volt offers three driver-selected modes: normal, sport, and mountain; mountain mode is designed to help the Volt traverse particularly steep and long grades. This mode increases minimum battery SOC to around 45%. The driver

will hear more engine noise during mountain mode, due to the higher rate of power generation required to maintain this mode. GM expects mountain mode to be required only under unusual power demand conditions.

### **Battery**

The Volt's lithium-ion battery (Li-ion) battery pack weighs 435 lb (197 kg) and consists of 288 individual cells arranged into nine modules. Plastic frames hold pairs of lithium-ion cells that sandwich an aluminum cooling fin [30]. The design and construction of that aluminum plate was critical to ensuring an even temperature distribution with no hot or cool spots across the flat, rectangular cell. The battery pack has its own cooling circuit that is similar to, but independent from, the engine cooling system. The battery's shape is shown in fig. 30.

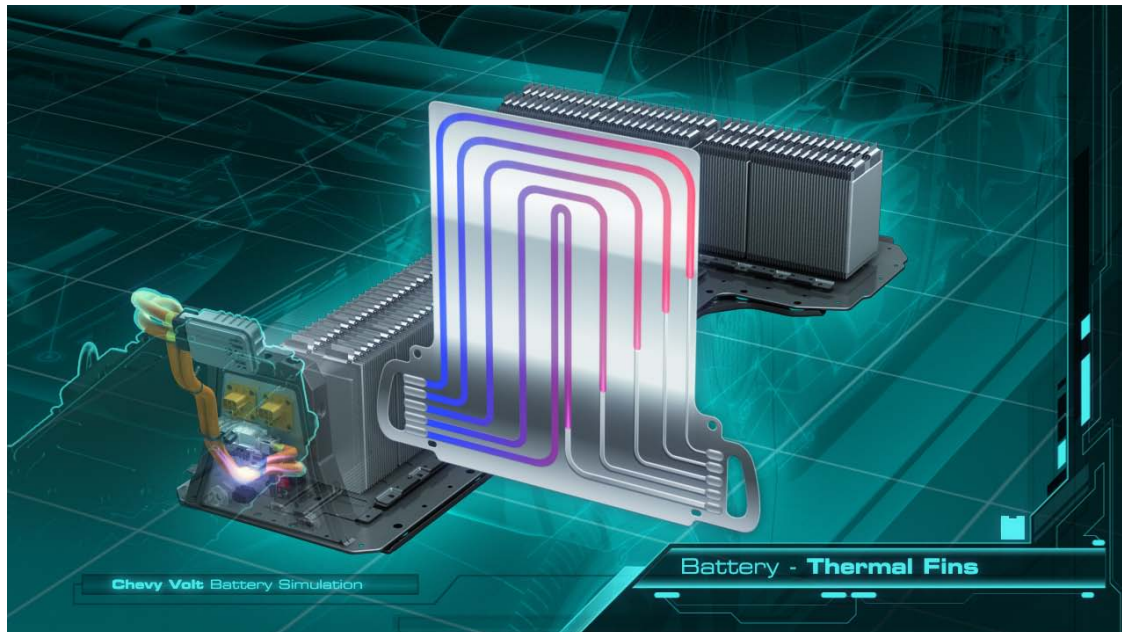


**Figure 30** Chevrolet Volt battery design.

The Dana Corp-manufactured cooling fin consists of two lightweight aluminum plates joined by a proprietary clean nickel-brazing process. The carefully designed grooves stamped into the plates form channels that allow battery coolant that is pumped through the pack to flow over the entire cell surface. In fig. 31 the aluminum foil is shown.

Three different systems are used to regulate the temperature of the coolant. When the Volt is plugged in and charging in cold weather, an electric heater at the front of the battery pack is used to warm the coolant and pre-heat the battery. During normal operations, the coolant is passed through a heat exchanger

at the front of the car, while a chiller in the air conditioning circuit can be used to dissipate heat from the battery when temperatures really climb.



**Figure 31** Aluminum foil.

The battery pack stores 16 kW·h of energy but it is controlled or buffered via the energy management system to use only 10.4 kW·h of this capacity to maximize the life of the pack. For this reason the battery pack never fully charges or depletes, as the software only allows the battery to operate within a state of charge (SOC) window of 65%, after which the engine kicks in and maintains the charge near the lower level. The minimum SOC varies depending on operating conditions. When more power is required, such as mountain mode, the lower limit of the SOC will raise to 45% to ensure there is enough power available.

Because batteries as described before are sensitive to temperature changes, the Volt has a thermal management system to monitor and maintain the battery pack temperature for optimum performance and durability. The Volt's battery pack provides reliable operation, when plugged in, at temperatures as low as -13 °F (-25 °C) and as high as 122 °F (50 °C). Because the Volt features a battery pack that can be warmed or cooled, in cold weather the battery is preheated during charging to provide full power capability; in hot weather the battery can be cooled during charging. The Volt's thermal management system can also be powered during driving either by the battery or en-



gine. The management system monitors feedback from 16 thermal sensors arranged throughout the battery pack to maintain a spread of no more than 2 degrees centigrade from the optimal temperature across the pack.

The Volt's battery is guaranteed by General Motors for eight years or 100,000 miles (160,000 km), and will cover all 161 battery components. As all rechargeable batteries degrade over time, General Motors estimates the Volt battery will degrade by 10 to 30% after 8 to 10 years. The Volt's battery management system runs more than 500 diagnostics at 10 times per second, allowing to keep track of the Volt's battery pack in real-time, 85% of which ensure the battery pack is operating safely and 15% monitor battery performance and life.

The Volt uses a new plug specification, SAE J1772-2009, that is being proposed as a standard for electric cars. A full charge takes approximately ten to twelve hours from a standard North American 120V, 15 A household outlet and about three hours from a standard 240 VAC outlet.

### 3.2 Nissan Leaf



**Figure 32** Nissan Leaf.

The Nissan Leaf is a five-door hatchback electric car manufactured by Nissan and introduced in Japan and the United States in December 2010. The US Environmental Protection Agency official range is 117 kilometres (73 mi), with an energy consumption of 765 kilojoules per kilometre (34 kW·h/100 mi) and rated the Leaf's combined fuel economy at 99 miles per gallon gasoline equivalent.

lent (2.9 litre/100km). The Leaf has a range of 175 km (109 mi) on the New European Driving Cycle.

As an all-electric car, the Nissan Leaf produces no tailpipe pollution or greenhouse gas emissions at the point of operation, and reduces dependence on petroleum. Among other awards and recognition, the Nissan Leaf won the 2010 Green Car Vision Award award, the 2011 European Car of the Year award, the 2011 World Car of the Year, and ranks as the most efficient EPA certified vehicle for all fuels ever.

### **3.2.1 Specifications**

#### ***Powertrain***

Nissan says that the car has a top speed of over 150 km/h (93 mph). Its motor is rated at 80 kilowatts (110 hp) and 280 newton meters (210 lb·ft). Unofficially, 0 to 60 mph (0 to 97 km/h) performance has been tested at 9.9 seconds. The Leaf uses a front-mounted electric motor driving the wheels, powered by a 86 megajoules (24 kW·h) lithium ion battery pack rated to deliver up to 90 kilowatts (120 hp) power. The pack contains air-cooled, stacked laminar battery cells with lithium manganate cathodes. The battery and control module together weigh 300 kilograms (660 lb) and the specific energy of the cells is 140 W·h/kg. Each battery pack costs Nissan an estimated US\$18,000 (as of May 2010). Under its five-cycle testing, the United States Environmental Protection Agency found the Leaf's energy consumption to be 765 kJ/km (34 kWh/100 miles) and rated the Leaf combined fuel economy equivalent at 99 MPGe (2.4 L/100 km), with an equivalent 106 mpg-US (2.22 L/100 km; 127 mpg-imp) in city driving and 92 mpg-US (2.6 L/100 km; 110 mpg-imp) on highways.

#### ***Battery***

The 24 kWh battery pack consists of 48 modules and each module contains four cells, a total of 192 cells, and is assembled by Automotive Energy Supply Corporation (AESC) – a joint venture between Nissan, NEC and NEC Energy Devices, at Zama, Japan. Since the battery is the heaviest part of any EV, Nissan housed the battery pack below the seats and rear foot space to keep the center of gravity as low as possible and also results in increased structural rigidity as compared to a conventional five-door hatchback.

The battery pack is expected to retain 70% to 80% of its capacity after 10 years but its actual lifespan depends on how often fast charging (440-volt) is used and also on environmental factors. Nissan stated the battery has a "lifespan of 5–10 years under normal use". The Leaf's battery is guaranteed by Nissan for eight years or 100,000 miles (160,000 km).

In addition to the main battery, the Leaf also has an auxiliary 12-volt lead-acid battery that provides power to the car computer systems and accessories such as the audio system, supplemental restraint systems, headlights and windshield wipers. The small solar panel on the Leaf rear helps to charge this accessory battery. Fig 33 displays the Nissan Leaf battery.



**Figure 33** Nissan Leaf battery.

Nissan recommends owners the following preventive actions to help maximize the lithium-ion battery's useful life and its ability to hold a charge:

- Avoid exposing a vehicle to ambient temperatures above 120 °F (49 °C) for over 24 hours.
- Avoid storing a vehicle in temperatures below -13 °F (-25 °C) for over 7 days.
- Avoid exceeding 70 to 80% state of charge when using frequent (more than once per week) fast or quick charging.

- Allow the battery charge to be below at least 80% before charging.
- Avoid leaving the vehicle for over 14 days where the Li-ion battery available charge gauge reaches a zero or near zero (state of charge).

The Leaf has two charging receptacles: a standard SAE J1772-2009 connector for level 1 and 2 recharging (120/220 volts AC) and a JARI Level 3 DC connector designed by TEPCO for high-voltage, DC fast charging (480 volts DC 125 amps) that uses the CHAdeMO protocol.

Using the on-board 3.3 kW charger the Leaf can be fully recharged from empty in 8 hours from a 220/240-volt 30 amp supply (5.2 kW allowable draw) that can provide the on-board charger its full 3.3 kW of usable power.

In North America and Japan using a standard household outlet (120-volt, 15 amp breaker, 12 amp maximum allowable draw, 1.4 kW) and the 7.5-meter (25 ft) cable included by Nissan, the Leaf will regain approximately 5 miles of range per hour. This type of charging is intended for convenience use when making stops or for emergency charging if you are within a short range of the charging destination. Using DC fast charging, the battery pack can be charged to 80% capacity in about 30 minutes. Nissan developed its own 500-volt DC fast charger. Nissan warns that if fast charging is the primary way of recharging, then the normal and gradual battery capacity loss is about 10% more than regular 220-volt charging over a 10-year period.



### 3.3 Toyota Prius (XW30)



**Figure 34** Toyota Prius (XW30).

The Toyota Prius is a mid-size hatchback that has been produced by Toyota. Toyota debuted the third generation Prius (2010 US model year) at the January 2009 North American International Auto Show, and sales began in Japan on May 18, 2009. Replacing the XW20 series, the XW30 represents the third generation of the Toyota Prius. Its new body design is more aerodynamic, with the coefficient of drag reduced to 0.25 Cd. An underbody rear fin helps stabilize the vehicle at higher speeds.

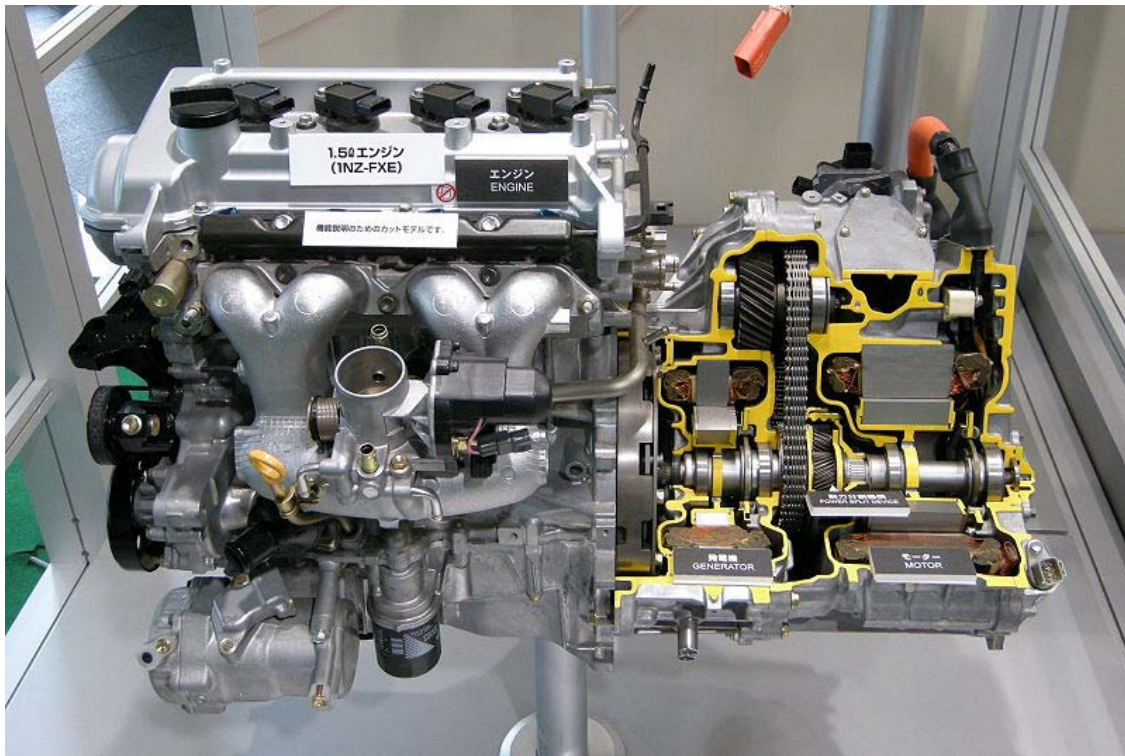
The estimated fuel-efficiency rating, using the U.S. EPA combined cycle, is 50 mpg-US (4.7 L/100 km; 60 mpg-imp). The Prius was the most efficient car powered by liquid fuel available in the U.S. in 2009, based on the official rating. Only the first-generation Honda Insight (2000–2006) equipped with a manual transmission attained a lower fuel consumption rate. The official UK fuel efficiency data for the Prius T3 is Urban 72.4 mpg-imp (3.90 L/100 km; 60.3 mpg-US), Extra Urban 76.4 mpg-imp (3.70 L/100 km; 63.6 mpg-US), Combined 72.4 mpg-imp (3.90 L/100 km; 60.3 mpg-US).

The Prius facilitates the Toyota Hybrid Synergy Drive technology.

### 3.3.1 Toyota Hybrid Synergy Drive

#### *Drivetrain*

The Toyota HSD replaces a normal geared transmission with an electromechanical system. Because an internal combustion engine (ICE) delivers power best only over a small range of torques and speeds, the crankshaft of the engine is usually attached to an automatic or manual transmission by a clutch or torque converter that allows the driver to adjust the speed and torque that can be delivered by the engine to the torque and speed needed to drive the wheels of the car. When required to classify the transmission type of an HSD vehicle (such as in standard specification lists or for regulatory purposes), Toyota describes HSD-equipped vehicles as having an e-CVT (electronic continuously variable transmission). Fig. 35 presents a HSD engine with unshielded electric motor and generator and fig. 36 presents the Electronic continuously variable transmission (e-CVT) of the HSD.

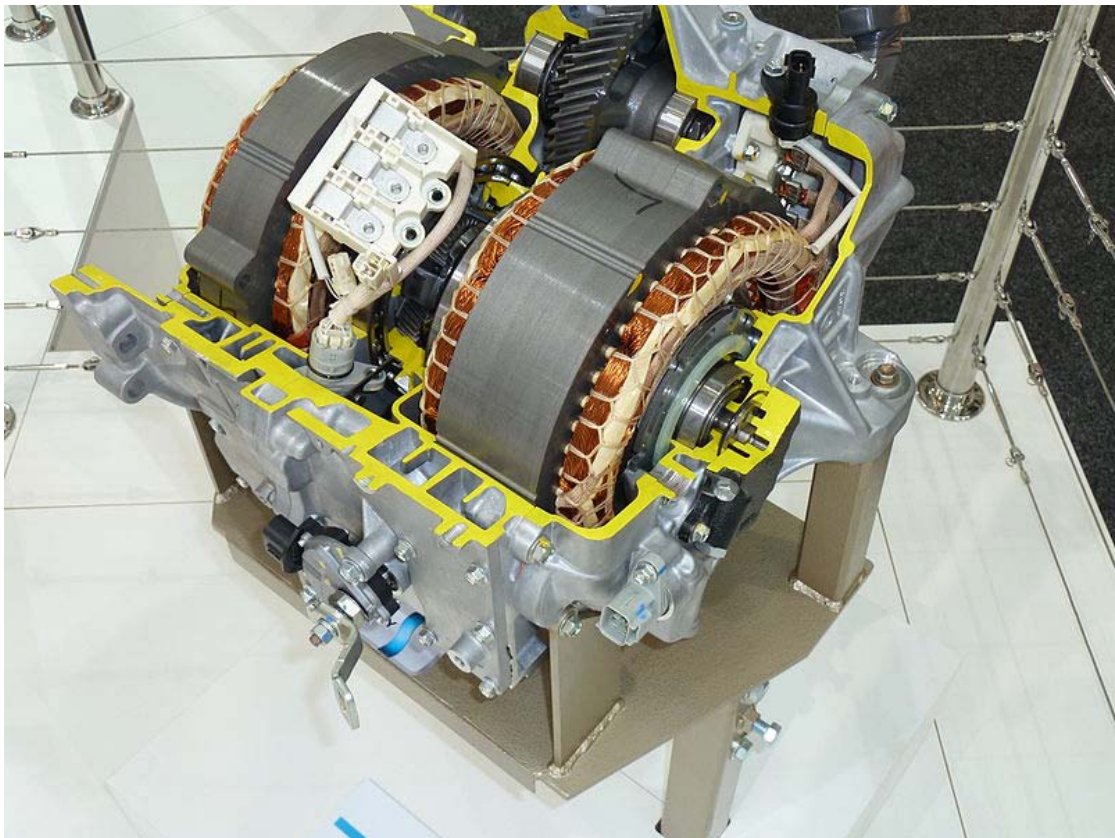


**Figure 35** HSD engine with unshielded electric motor and generator.

In the "standard" car design the alternator (AC generator) and starter (DC motor) are considered accessories that are attached to the internal combustion engine (ICE) which normally drives a transmission to power the wheels propelling the vehicle. A battery is used only to start the car's internal combustion en-



gine and run accessories when the engine is not running. The alternator is used to recharge the battery and run the accessories when the engine is running. HSD replaces the gear box (transmission), alternator and starter motor with a pair of powerful motor-generators (designated MG1 and MG2, ~80 Hp total) with a computerized shunt system to control them, a mechanical power splitter that acts as a second differential, and a battery pack that serves as an energy reservoir. The motor-generator uses power from the battery pack to propel the vehicle at startup and at low speeds or under acceleration. The ICE may or may not be running at startup. When higher speeds, faster acceleration or more power for charging the batteries is needed the ICE is started by the motor-generator (acting as a starter). These features allow the ICE to normally be turned off for traffic stops—accessory power (including air conditioning if needed) is normally provided by the battery pack.



**Figure 36** Electronic continuously variable transmission (e-CVT).

When a moving vehicle operator wants the vehicle to slow down the initial travel of the brake pedal engages the motor-generator(s) into generator mode converting much of the forward motion into electrical current flow which is used

to recharge the batteries while slowing down the vehicle. In this way the forward momentum regenerates (or converts) much of the energy used to accelerate the vehicle back into stored electrical energy. Harder braking action engages standard front disk and rear drum (rear disk for 2010 and later models) brakes which are also provided for faster stops and emergency use. This wastes energy which could have been recovered and is discouraged for normal use.

MG1 (motor generator 1): generates electrical power. MG1 recharges the EV battery and supplies electrical power to drive MG2. In addition, by regulating the amount of electrical power generated (thus varying MG1's internal resistance and rpm), MG1 effectively controls the transaxle's continuously variable transmission. MG1 also serves as the engine starter.

MG2 (motor generator 2): drives the vehicle. MG2 and the engine work together to drive the wheels. The addition of MG2's strong torque characteristics help achieve excellent dynamic performance, including smooth start-off and acceleration. During regenerative braking, MG2 converts kinetic energy into electrical energy, which is then stored in the EV battery.

### ***Transmission***

The mechanical gearing design of the system allows the mechanical power from the ICE to be split three ways: extra torque at the wheels (under constant rotation speed), extra rotation speed at the wheels (under constant torque), and power for an electric generator. A computer program running appropriate actuators controls the systems and directs the power flow from the different engine + motor sources. This power split achieves the benefits of a continuously variable transmission (CVT), except that the torque/speed conversion uses an electric motor rather than a direct mechanical gear train connection. An HSD car cannot operate without the computer, power electronics, battery pack and motor-generators, though in principle it could operate while missing the internal combustion engine. In practice, HSD equipped cars can be driven a mile or two without gasoline, as an emergency measure to reach a gas station.

An HSD transaxle contains a planetary gear set that adjusts and blends the amount of torque from the engine and motor(s) as it's needed by the front wheels. It is a sophisticated and complicated combination of gearing, electrical motor-generators and computer controlled electronic controls. One of the motor-

generators (MG2 in Toyota manuals; sometimes called "MG-T" for "Torque") is mounted on the drive shaft, and thus couples torque into or out of the drive shafts: feeding electricity into MG2 adds torque at the wheels. The engine end of the drive shaft has a second differential; one leg of this differential is attached to the internal combustion engine and the other leg is attached to a second motor-generator (MG1 in Toyota manuals; sometimes "MG-S" for "Speed"). The differential relates the rotation speed of the wheels to the rotation speeds of the engine and MG1, with MG1 used to absorb the difference between wheel and engine speed. The differential is an epicyclic gear set (also called a "power split device"); that and the two motor-generators are all contained in a single transaxle housing that is bolted to the engine. Special couplings and sensors monitor rotation speed of each shaft and the total torque on the drive shafts, for feedback to the control computer.

### ***Operation***

The HSD drive works by shunting electrical power between the two motor generators, running off the battery pack, to even out the load on the internal combustion engine. Since a power boost from the electrical motors is available for periods of rapid acceleration, the ICE can be downsized to match only the average load on the car, rather than sized by peak power demands for rapid acceleration. The smaller internal combustion engine can be designed to run more efficiently. Furthermore, during normal operation the engine can be operated at or near its ideal speed and torque level for power, economy, or emissions, with the battery pack absorbing or supplying power as appropriate to balance the demand placed by the driver. During traffic stops the internal combustion engine can even be turned off for even more economy.

The combination of efficient car design, regenerative braking, turning the engine off for traffic stops, significant electrical energy storage and efficient internal combustion engine design give the HSD powered car significant efficiency advantages—particularly in city driving.

### ***Phases of operation***

The HSD operates in distinct phases depending on speed and demanded torque. Here are a few of them:

Engine start: To start the engine, power is applied to MG1 to act as a starter. Because of the size of the motor generators, starting the engine requires relatively little power from MG1 and the conventional starter motor sound is not heard. Engine start can occur while stopped or moving.

Low gear (equivalent): When accelerating at low speeds in normal operation, the engine turns more rapidly than the wheels but does not develop sufficient torque. The extra engine speed is fed to MG1 acting as a generator. The output of MG1 is fed to MG2, acting as a motor and adding torque at the drive-shaft.

High gear (equivalent): When cruising at high speed, the engine turns more slowly than the wheels but develops more torque than needed. MG2 then runs as a generator to remove the excess engine torque, producing power that is fed to MG1 acting as a motor to increase the wheel speed. In steady state, the engine provides all of the power to propel the car unless the engine is unable to supply it (as during heavy acceleration, or driving up a steep incline at high speed). In this case, the battery supplies the difference. Whenever the required propulsion power changes, the battery quickly balances the power budget, allowing the engine to change power relatively slowly.

Reverse gear: There is no reverse gear as in a conventional gearbox: the computer feeds negative voltage to MG2, applying negative torque to the wheels. Early models did not supply enough torque for some situations: there have been reports of early Prius owners not being able to back the car up steep hills in San Francisco. The problem has been fixed in recent models. If the battery is low, the system can simultaneously run the engine and draw power from MG1, although this will reduce available reverse torque at the wheels.

Silent operation: At slow speeds and moderate torques the HSD can drive without running the internal combustion engine at all: electricity is supplied only to MG2, allowing MG1 to rotate freely (and thus decoupling the engine from the wheels). This is popularly known as "Stealth Mode". Provided that there is enough battery power, the car can be driven in this silent mode for some miles even without gasoline.

Neutral gear: Most jurisdictions require automotive transmissions to have a neutral gear that decouples the engine and transmission. The HSD "neutral

gear" is achieved by turning the electric motors off. Under this condition, the planetary gear is stationary (if the vehicle wheels are not turning); if the vehicle wheels are turning, the ring gear will rotate, causing the sun gear to rotate as well (the engine inertia will keep the carrier gear stationary unless the speed is high), while MG1 freewheels so no power is dissipated.

**Regenerative braking:** By drawing power from MG2 and depositing it into the battery pack, the HSD can simulate the deceleration of normal engine braking while saving the power for future boost. The regenerative brakes in an HSD system absorb a significant amount of the normal braking load, so the conventional brakes on HSD vehicles are undersized compared to brakes on a conventional car of similar mass.

**Engine braking:** The HSD system has a special transmission setting labelled 'B' (for Brake), that takes the place of a conventional automatic transmission's 'L' setting, providing engine braking on hills. This can be manually selected in place of regenerative braking. During braking when the battery is approaching potentially damaging high charge levels, the electronic control system automatically switches to conventional engine braking, drawing power from MG2 and shunting it to MG1, speeding the engine with throttle closed to absorb energy and decelerate the vehicle.

**Electric boost:** The battery pack provides a reservoir of energy that allows the computer to match the demand on the engine to a predetermined optimal load curve, rather than operating at the torque and speed demanded by the driver and road. The computer manages the energy level stored in the battery, so as to have capacity to absorb extra energy where needed or supply extra energy to boost engine power.

**Battery charging:** The HSD can charge its battery without moving the car, by running the engine and extracting electrical power from MG1. The power gets shunted into the battery, and no torque is supplied to the wheels.

### **3.3.2 Specifications**

The 1.8-liter four-cylinder gasoline engine (previously 1.5 liters) generates 98 hp (73 kW; 99 PS), and with the added power of the electric motor 80hp (60kw), total horsepower is 134 hp (100 kW; 136 PS) (previously 110 hp). The

larger engine displacement allows for increased torque, reducing engine speeds (RPM), which increases fuel economy at highway speeds. With an electric water pump, the Prius engine is the first production engine that requires no accessory belts, which also further improves fuel economy. The electric motors and other components of the hybrid powertrain are also smaller and more efficient. Toyota estimates the new inverter, motor and transaxle are 20 percent lighter. It has a 1.4 kWh NiMH battery.

The following table 8 contains collective information for the three models.

**Table 8** Information for the three models.

<b>Specifications</b>	<b>Chevrolet Volt</b>	<b>Nissan Leaf</b>	<b>Toyota Prius (XW30)</b>
<b>ICE</b>	1,4 L (4-cylinder 80hp)	-	1,8 L (4-cylinder 98 hp)
<b>Electric Motor</b>	111 kW (149 hp) / gen 55kw (74 hp)	80 kw (110 hp)	60 kw (80 hp)
<b>Battery</b>	Li-ion (16 kWh)	Li-ion (24 kWh)	Ni-MH (1.4 kWh)
<b>All Electric Range</b>	56 km	117 km	-
<b>Mpg-e (collective) EPA</b>	60	99	50

## 4 Comparison

Now that the three models have been presented a comparison of the three architecture efficiencies can be made. The efficiencies found will incorporate the efficiencies of fuel production, for electricity generation and oil production, so a more clear understanding of the total efficiency and viability of these vehicles is provided.

Since these are actual cars that have entered the market in the last year there is no clear information on all the specific values of their components. As a consequence for the comparison typical nominal values for similar components will be used. The efficiency of an internal combustion engine is chosen to be 25%. Moreover the inverters are chosen to have 96% efficiency. The generator



is assumed to have an efficiency of 95%. For the electric motors the following table 9 will be used for acquiring the efficiency [31].

**Table 9** Nominal Efficiency for given power.

Power (hp)	Nominal efficiency
1-4	78.8
5-9	84
10-19	85.5
20-49	88.5
50-99	90.2
100-124	91.7
>125	92.4

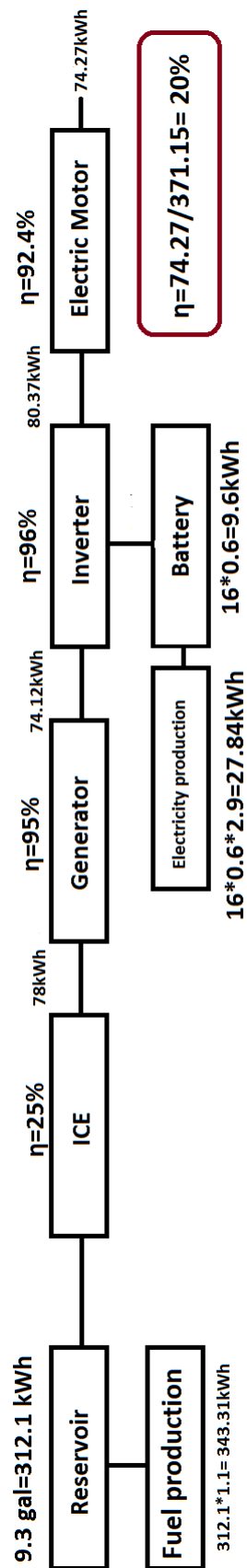
The losses of the battery are supposed to be zero because these cars have top technology batteries and the information for their losses is not released. Moreover since the efficiency of the gears is also not given, the output of the system in order to find the efficiency is considered right before the gear set.

To calculate the input energy the tank size of each car and the battery size were used. In order to take into account the impact of electricity generation and oil fuel production in the equation, the energy values were converted to primary energy. The primary energy factor for electricity in Greece is 2.9 and for the gasoline is 1.1. The Chevrolet Volt has a 9.3 gallon tank and the Prius has a 12.9 gallon tank. In order to calculate the energy content these values were multiplied by 33.56 to find the energy in kWh.

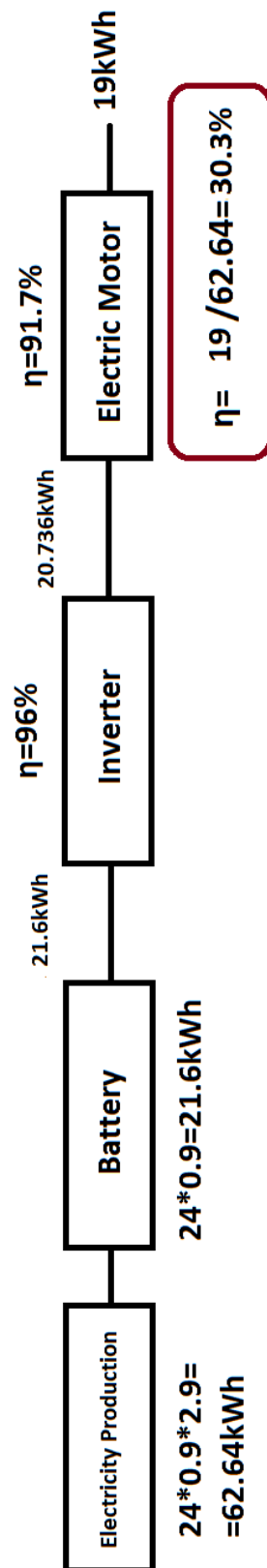
In the previous chapters it was described that the batteries of electric vehicles never get completely charged or discharged. For the Volt the battery has a threshold of 25-85% that is why 60% of battery content was used for the calculations. Nissan Leaf is an electric vehicle and these vehicles use 90% of the battery content and that was used for the calculations. The Prius battery simulations has shown that about 0.3 to 0.5 kWh are usually used and also Prius is not a plug-in. As such 0.5kwh were used for the calculations.

Chevrolet Volt has many different operating modes but for the calculations the most representing operating mode was used. For this reason mode 3 as presented in the previous chapter was used.

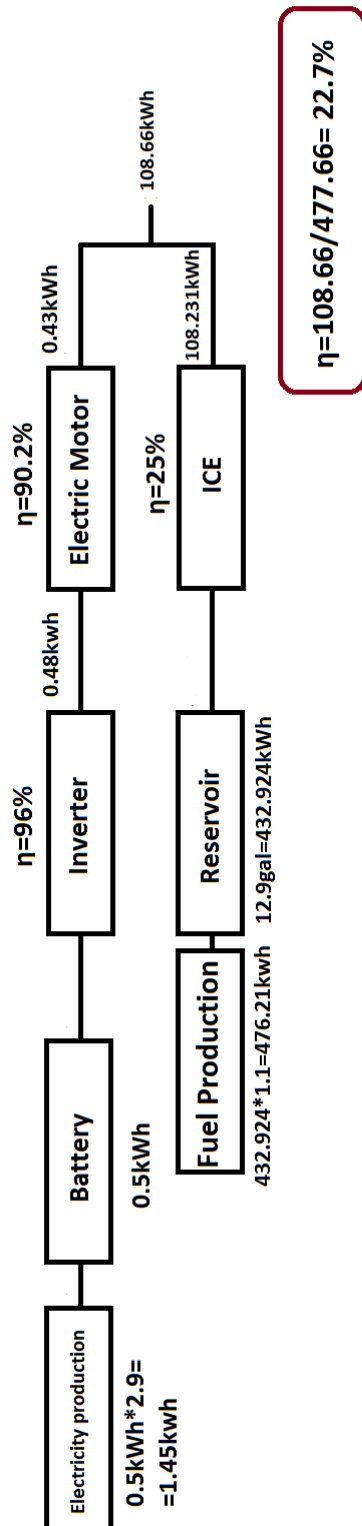
In the following figures 37, 38 and 39 the process of calculating the efficiency of Chevrolet Volt, Nissan Leaf and Toyota Prius respectively is presented.



**Figure 37** Chevrolet Volt efficiency calculation.



**Figure 38** Nissan Leaf efficiency calculation.



**Figure 39** Toyota Prius efficiency calculation.

The results do not stray much from the EPA's mpg-e tables. However this is a very simplified approach and does not represent the actual efficiencies because many parameters are not accounted for like real efficiency values for components, different driving modes, energy recovery methods (e.g. regenerative braking) and other.

The results are 20% , 30.3% and 22.7% efficiency for Chevrolet Volt, Nissan Leaf and Toyota Prius respectively. The Nissan Leaf has a higher efficiency because there is no internal combustion engine, however the output is significantly lower than the other two cars which means that it has a much lower range and as such needs more refueling (or rather recharging). Also Volt has a lower efficiency than Prius because of the many energy conversions.

## **5 Impacts and future of electric vehicles**

In this chapter the impacts of electric vehicle introduction to transportation options are presented as well as an outlook for the future development.

### **5.1 Emissions**

Electric-drive vehicles (EVs) are widely promoted for their environmental and energy efficiency benefits. However, unlike conventional gasoline vehicles, whose emissions of greenhouse gases (GHGs) are a combination of “upstream” emissions from fuel production and distribution and “downstream” emissions from vehicle operation, emissions from EVs are more heavily or even entirely upstream in the fuel production and distribution process. In some ways this makes emissions from these vehicles easier to make an approximation, but there still are many complexities involved. This is particularly true for “plug-in hybrid” vehicles (or “PHEVs”) that use a combination of grid electrical power and another fuel that is combusted onboard the vehicle.

PHEVs with true “all-electric range” (AER) could permit drivers to some trips without the engine turning on at all (or at least very little), where the trip can be made almost entirely on the energy stored in the battery. However, some PHEVs are not designed for this and instead employ “blended mode” operation, where the design would be for the engine to turn off and on sporadically. And in other cases, even for “series type” PHEVs with extensive AER, some engine operation is to be expected both on longer trips and in other cases where the PHEV battery becomes discharged before it can be charged again.

In the case of battery electric vehicles (BEVs) and fuel cell vehicles (FCVs), the emissions from the vehicles are entirely dependent on the method with which the electricity and/or hydrogen (H<sub>2</sub>) are produced, along with the energy-use efficiency of the vehicle (typically expressed in “watt hours per mile/kilometer” for BEVs and “miles/kilometers per kilogram” for H<sub>2</sub>-powered vehicles). In the case of PHEVs, an upstream emission component results from the use of electricity from the wall plug or charger (along with upstream emissions from the production of the vehicle’s other fuel), but there can be also significant tailpipe emissions depending on travel patterns and the type of plug-in hybrid.

GHG emissions from conventional and alternative vehicles have been broadly studied over the past 20 or more years, but are still not fully understood and accounted for. This is particularly so with regard to some of the subtler aspects of vehicle three-way catalyst operation and emissions of trace gases, as well as some potentially important nuances of upstream emissions from virtually all fuels due to the complication of estimating various aspects of upstream emissions. These include, for example, difficulty in precisely assessing the true marginal emissions impacts from the increased use of power plants to charge BEVs and PHEVs, and some secondary aspects of upstream emissions that can be important such as the “indirect land use” change effects of the production of biomass for biofuel vehicles. GHG emission reductions from vehicles and fuels represent an important set of strategies for reducing emissions from the transportation sector, among various other options.

Additionally, some aspects of climate dynamics are still not completely understood, for example, with regard to the exact “radiative forcing” aspects of

certain gases emitted by vehicles, especially fine particulates and conventional pollutants that appear to have relatively weak impacts but of uncertain magnitude and potentially even uncertain direction. This renders some uncertainty in the overall impacts of the GHGs that are compounded by uncertainties in the exact levels of emissions themselves.

#### **5.1.1 Formation of GHG emission from EV fuel cycles**

A key feature of GHG emissions from the production of transportation fuels and electricity is that emissions of CO<sub>2</sub> are relatively easy to estimate: they can be approximated as the carbon content of the fuel multiplied by 3.66 (the ratio of the molecular mass of CO<sub>2</sub> to the molecular mass of carbon), on the assumption that virtually all of the carbon in fuel oxidizes to CO<sub>2</sub>.

On the contrary, combustion emissions of all the other GHGs are a function of many complex aspects of combustion dynamics (such as temperature, pressure, and air-to-fuel ratio) and of the type of emission control systems used, and hence cannot be derived from one or two basic characteristics of a fuel. Instead, one must use published emission factors for each combination of fuel, end-use technology, combustion conditions, and emission control system. Likewise, non-combustion emissions of GHGs (e.g., gas flared at oil fields or N<sub>2</sub>O produced and emitted from fertilized soils), cannot be derived from basic fuel properties, and instead must be measured and estimated source-by-source and gas-by-gas.

As indicated above, GHG emissions from the life cycle of fuels for BEVs and H<sub>2</sub> fuel cell EVs are entirely in the form of upstream emissions, with no emission from the vehicles themselves (except for water vapor in the case of FCVs). As such, the GHG emissions from battery and fuel cell EVs are completely related to the fabrication of electricity or H<sub>2</sub>. Emissions from electricity generation processes are generally well known and well studied; this is less true for H<sub>2</sub> production but in most cases these emissions are well understood as well. Some innovative H<sub>2</sub> production methods, and those that are based on conversion from biofuels, have somewhat complex and definitely not completely understood and established levels of emissions of GHGs.



In contrast, for PHEVs, emissions are a complex combination of upstream and in-use emissions. Emissions from these vehicles are more complicated than for conventional vehicles or EVs, because these vehicles combine features of internal combustion engine vehicles (ICEVs) with those of EVs. Various vehicle design and operational strategies are available for PHEVs, and these can have important emissions implications. For example, PHEVs can be designed to be either “charge depleting (CD)” or “charge sustaining (CS)” and this affects the relative levels of electricity and gasoline used.

### **Upstream emissions**

The emissions associated with fuel production or “upstream” emissions dominate the fuel cycles associated with BEVs and FCVs. Other emissions are possible—for example, FCVs produce water vapor, which is a weak GHG but produced in amounts by FCVs that are very small in a relative sense to the global hydrologic cycle and not unlike water vapor emissions as a combustion product from conventional vehicles.

For PHEVs, total emissions consist of a mix of upstream emissions from electricity generation (proportional to the extent that the vehicle is recharged with electricity) and both upstream and in-use emissions from fuel combustion. For BEVs, upstream emissions consist of emissions from the production and delivery of electricity for vehicle charging. These emissions vary regionally, due to the fuels and types of power plants used to generate electricity. Finally, for FCVs, emissions are again entirely upstream from the production, delivery, and dispensing of gaseous or liquid H<sub>2</sub> (again with the exception of small amounts of water vapor that are emitted directly from FCVs exhaust systems).

### **Combustion or “in-use” emissions**

Emissions of GHGs from engine combustion processes result from a complex combination of combustion dynamics and emission controls, and vary widely by fuel type, engine operation, and emission control system applied (if any). For EVs, combustion emissions from the vehicle are limited to PHEVs that either use a combustion engine and generator as a “range extended” for what is fundamentally an EV driveline, or where the engine is connected in parallel to the driveline with the electric motor. Either way, the combustion engine operates sporadically to supplement the electric motor operation, and thereby produces

GHG emissions. The only other combustion emissions that might be expected from EVs are from those that might include a supplemental fuel-fired heater for the passenger cabin, for occasional use in colder climates. For BEVs and FCVs, combustion emissions are upstream only because these vehicles operate entirely on electric propulsion.

Key GHG emission products from combustion engines include CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, CO, NO<sub>x</sub>, soot, and various air toxics and other trace chemicals that can play roles in the formation of secondary particulates and other gases (such as ozone [O<sub>3</sub>]) that are known to have climatic effects. Additional in-use emissions include those that can occur from vehicle air-conditioning systems, where GHGs are often used as refrigerants.

### **Emissions of CO<sub>2</sub> and other GHGs from the vehicle life cycle**

What we call “the vehicle life cycle” includes the life cycle of the materials that compose a vehicle and the life cycle of the vehicle itself. The life cycle of automotive materials, such as steel, aluminum, and plastics, extends from production of raw ore to delivery of finished materials to assembly plants, and includes recycled materials as well as materials made from “virgin” ore. The life cycle of the vehicle itself comprises of vehicle assembly, transportation of finished motor vehicles and motor-vehicle parts, and vehicle disposal.

In the vehicle life cycle there are two broad sources of GHG emissions, similar to the emissions sources in the industrial sector in general: emissions related to the use of process energy (e.g., fuels burned in industrial boilers to provide process heat), and noncombustion emissions from process areas (e.g., emissions from the chemical reduction of alumina to aluminum, or NMHC emissions from painting auto bodies). Energy use and process areas can produce CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, CO, NMHCs, SO<sub>x</sub>, NO<sub>x</sub>, particulate matter (PM), and other pollutants relevant to life cycle analysis (LCA) of CO<sub>2</sub> GHG emissions. The most extensive of the vehicle life cycle assessment models include characterization of these vehicle manufacturing emissions and their contribution to the overall emissions from various vehicle/fuel life cycles. In general, manufacturing emissions can be somewhat higher for some types of EVs than for conventional vehicles (e.g., those that use large nickel-based batteries). The vehicle manufacturing emissions for EVs are often proportionately larger than for conventional vehicles be-

cause of their lower life cycle emissions. A key point is that because vehicle operational emissions dominate, EVs are often much cleaner than conventional vehicles in an overall sense even if they have slightly to somewhat higher vehicle manufacturing emissions.

## **5.2 Charging Infrastructure**

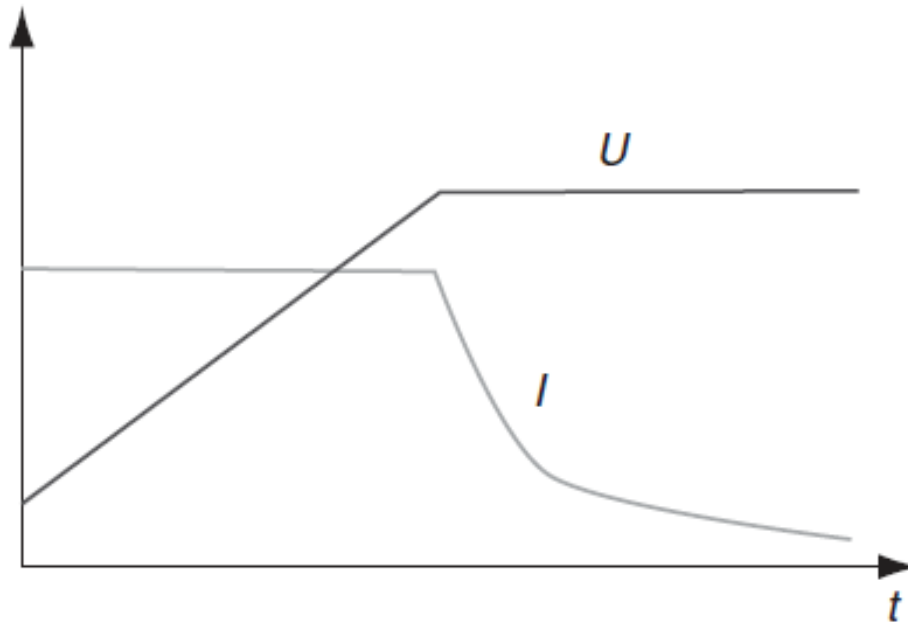
In urban traffic, due to their beneficial effect on environment, electrically propelled vehicles are an important factor for improvement of traffic and more particularly for a healthier living environment. The operation of the electrically propelled vehicle is dependent on the availability of efficient electric energy storage devices: the traction batteries. To allow the use of cheap and clean electric energy from the grid, recharging infrastructure shall be available to transfer electric energy from the distribution grid to the battery. This transfer can be done either by conduction or by induction, the first system being the most widely used.

### **Battery charging**

The process of battery charging typically involves two phases:

- The main charging phase, where the majority of energy is recharged into the battery
- The final charge phase, where the battery is conditioned and balanced

Most chargers in use today use the so-called IU characteristic, where a constant current  $I$  is used for the main charge and a constant voltage  $U$  for the final charge as shown in fig 40.



**Figure 40** IU charging characteristic.

The duration of the main charge phase depends on the available current and the rating of the charger, whereas the final charge, which only needs a small current, normally takes several hours. Opportunity charging, the partial charging used in public stations, mostly involves the main charge phase only. However, for a good maintenance of most types of battery, a periodical full charge is advisable.

### 5.2.1 Charging modes for conductive charging

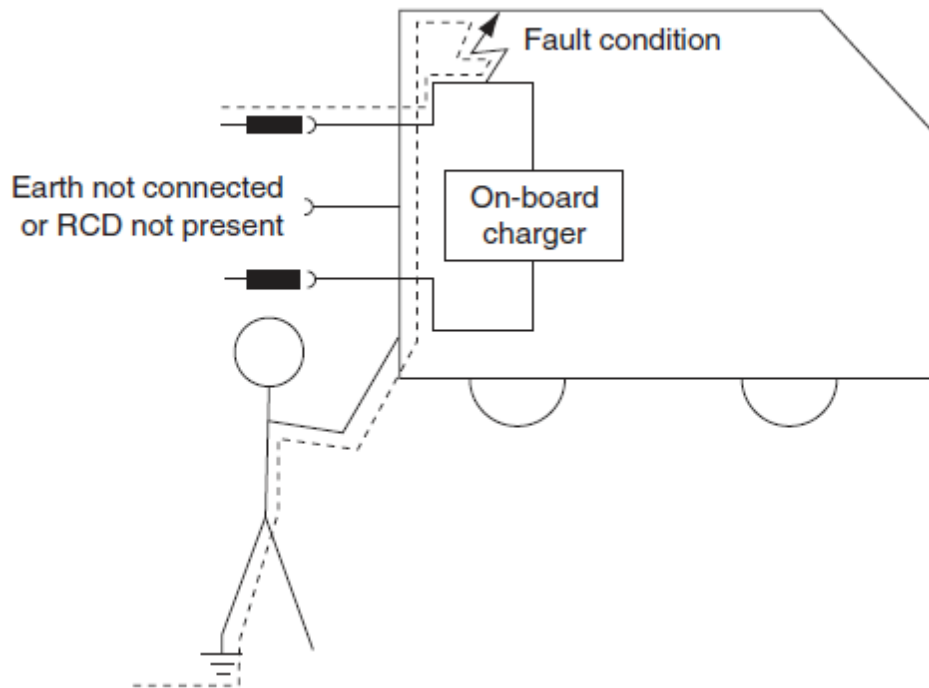
The infrastructure for charging is distinguished in modes.

#### **Mode 1**

Mode 1 charging refers to the connection of the electric vehicle to the a.c. supply network (mains) utilizing standardized socket outlets (i.e., meeting the requirements of any national or international standard), with currents up to 16 A. This corresponds to non-dedicated infrastructure, such as domestic socket outlets, to which electric vehicles are connected for charging. These socket outlets can easily and cheaply deliver the desired power, and due to their availability, Mode 1 charging is the most common option for electric vehicles, particularly when existing infrastructure is to be used.

However, a number of safety concerns must be taken into account. The safe operation of a Mode 1 charging point depends on the presence of suitable pro-

tections on the supply side: a fuse or circuit breaker to protect against overcurrent, a proper earthing connection, and a residual current device switching off the supply if a leakage current greater than a certain value (e.g., 30mA) is detected. Without proper earthing, a hazardous situation for indirect contact could occur with a single earth fault within the vehicle fig 41.



**Figure 41** Hazardous situation without RCD.

In most countries, residual current devices (RCDs) are now prescribed for all new electric installations. However, still a lot of older installations are lacking RCD, and it is often difficult for the electric vehicle's user to know, when plugging in the vehicle, whether or not an RCD is present. Whereas some countries leave this responsibility to the user, Mode 1 has therefore been outlawed in a number of countries such as the United States.

### ***Mode 2***

Mode 2 charging connection of the electric vehicle to the a.c. supply network (mains) also makes use of standardized socket outlets. It provides however additional protection by adding an in-cable control box with a control pilot conductor between the electric vehicle and the plug or control box.

The introduction of Mode 2 charging, mainly aimed at the United States, reflected the American infrastructure process which developed electrical standards and code language that were adopted by the National Electrical Code , to

ensure that personnel protection and other safety considerations were implemented in all charging systems utilized. Mode 2 was initially considered a transitional solution particularly for the United States, although it has received some new interest for replacing Mode 1 for charging at non-dedicated outlets. The main disadvantage of Mode 2 is that the control box protects the downstream cable and the vehicle, but not the plug itself, whereas the plug is one of the components more liable to be damaged in use.

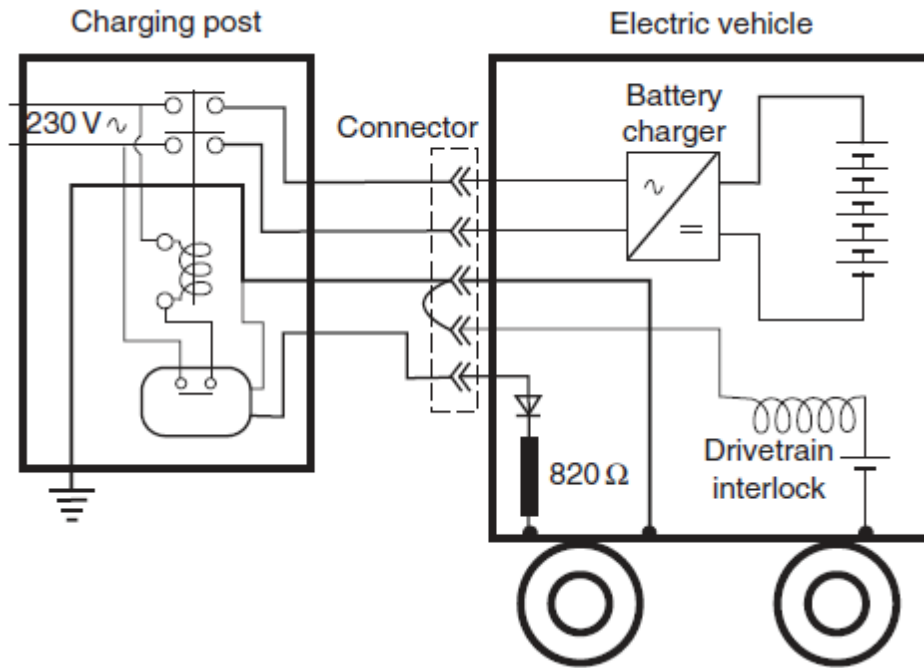
### ***Mode 3***

Mode 3 charging involves the direct connection of the electric vehicle to the a.c. supply network utilizing dedicated electric vehicle supply equipment. This refers to private or public charging stations. The standard IEC61851-1 mandates control pilot protection between equipment permanently connected to the a.c. supply network and the electric vehicle.

For Mode 3 charging, the IEC 61851-1 standard foresees additional protection measures to be provided by the so-called control pilot, a device which has the following functions mandated by the standard:

- Verification that the vehicle is correctly connected
- Continuous verification of the protective earth conductor integrity
- Energization and deenergization of the system
- Selection of charging rate

An example of control pilot circuit is given in fig. 42, showing the operation of the system. A small current is sent through the control pilot conductor, which is connected to the vehicle body by a resistor. The current returns to the charging post through the earth conductor. When the pilot current flows correctly, the contactor in the charging post is closed and the system is energized.



**Figure 42** Control pilot conductor.

When no vehicle is connected to the socket outlet, the socket is dead. This grants a key safety advantage particularly for publicly accessible charging points. Power is provided only when the plug is correctly inserted and the earth circuit is proved to be sound.

The connection process shall be such that the earth connection is made first and the pilot connection is made last. During disconnection, the pilot connection shall be broken first and the earth connection shall be broken last. This sequence also ensures that the current is interrupted at the contactor and not at the power contact pins of the plug, thus eliminating arcing and prolonging the service life of the accessories.

#### **Mode 4**

Mode 4 charging is defined as the indirect connection of the electric vehicle to the a.c. supply network (mains) utilizing an off-board charger where the control pilot conductor extends to equipment permanently connected to the a.c. supply. As the charger is located off-board, a communication link is necessary to allow the charger to be informed about the type and state of charge of the battery, so as to provide it with the right voltage and current. This pertains to d.c. charging stations, which are mostly used for fast charging.

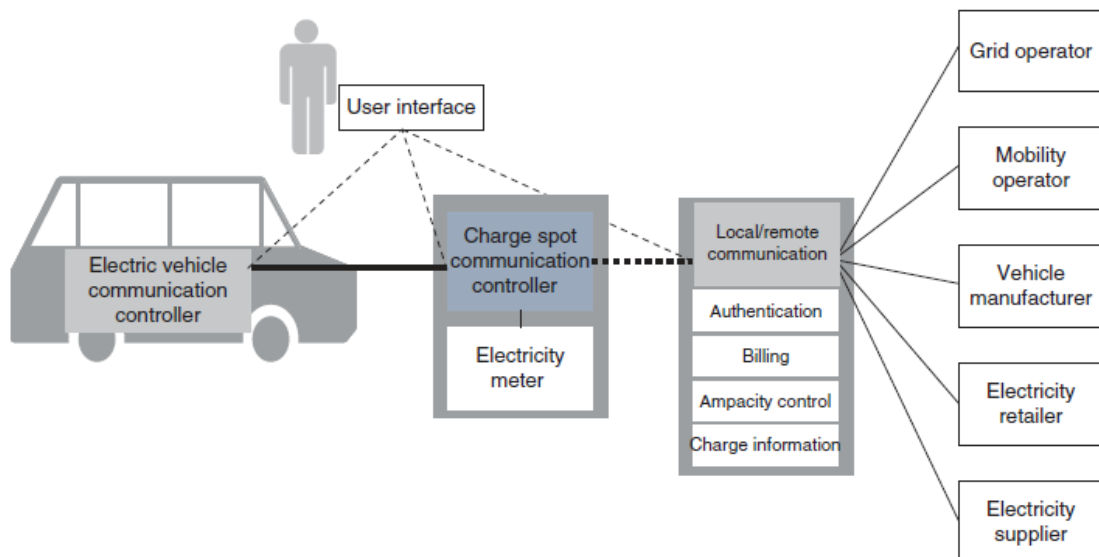
### ***Communication between control pilot and grid for grid management***

The development of new concepts such as “smart grid” or “vehicle to grid” has created the requirement for an appropriate communication protocol for electric vehicle charging beyond the mere safety functions of the control pilot, in order to provide functionalities such as:

- charge cost optimization by choosing the most appropriate time window where electricity rates are the lowest
- grid load optimization by controlling charger ampacity in function of grid demand
- vehicle identification and billing, allowing payment for charging at public charging stations, but also individual billing of used energy to the user’s account when the vehicle is charged at any outlets connected to a smart meter
- peak-shaving functionality by using electric vehicles connected to the grid as a spinning reserve (vehicle-to-grid)
- appropriate billing and user compensation functions for vehicle-to-grid operation

There are many individuals involved in the communication process. These actors include physical devices such as the charging post or the vehicle controller, individuals such as electricity suppliers or grid operators, and last but not least the vehicle user. An overview of individuals potentially involved and the communication links between them is shown in fig. 43. The local or remote communication system may have the function of a “clearing house” for the authentication, collecting and consolidation of grid and billing parameters from the individuals as well as transmitting charging process information to the respective individuals. Not all such functions are necessarily required for the basic charging functions, and some may be performed locally or remotely. The system can thus become rather complex, and several issues are still to be resolved.



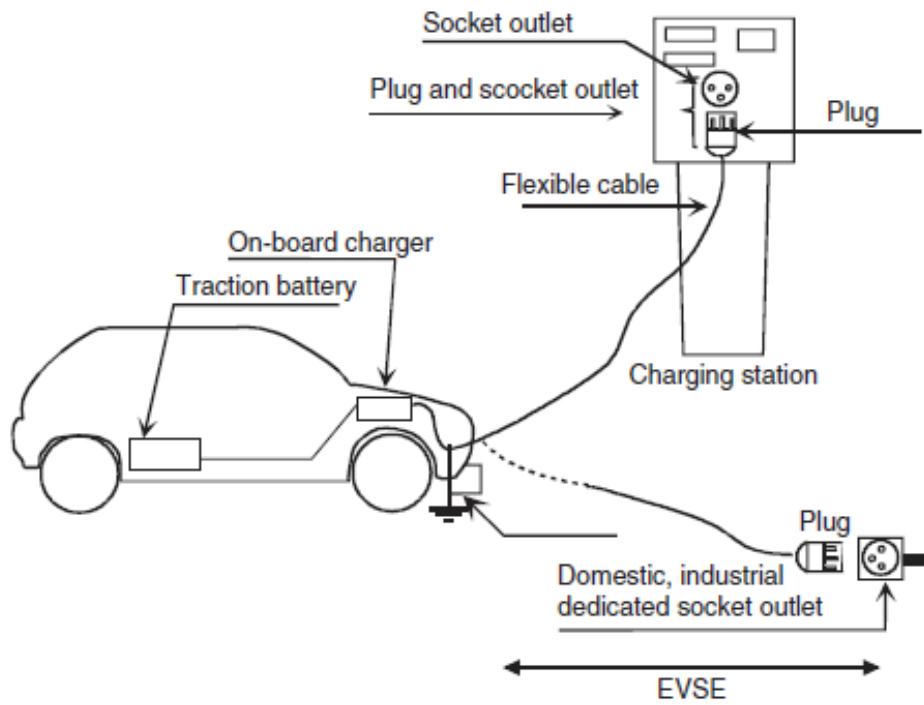


**Figure 43** Individuals involved in the charging process.

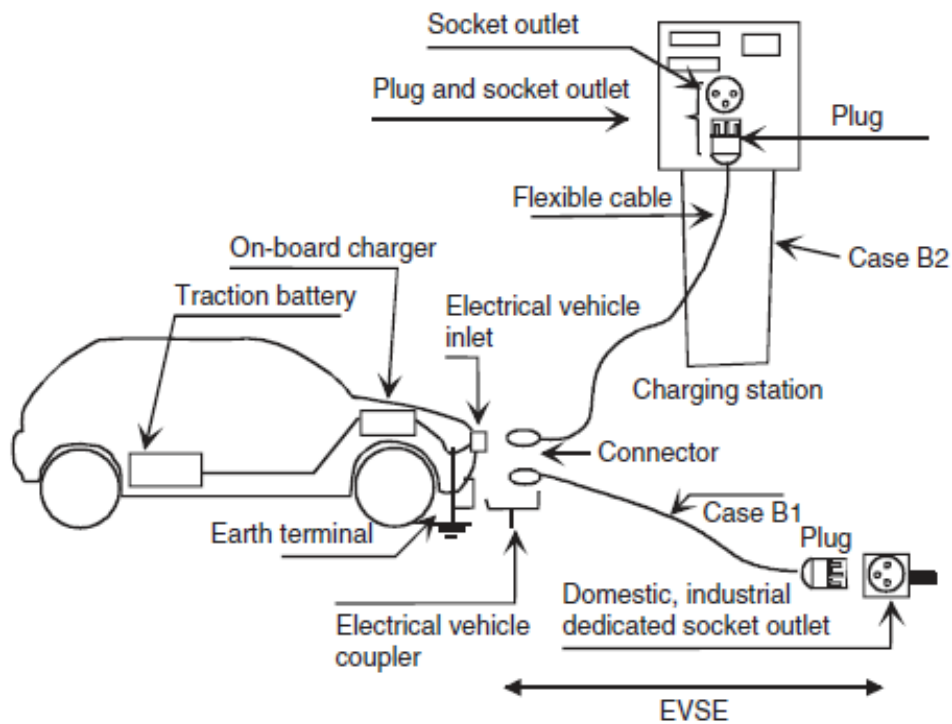
### ***Accessories for charging***

The connection of the cable between the vehicle and the charging outlet can be carried out in three ways as defined in IEC 61851-1 :

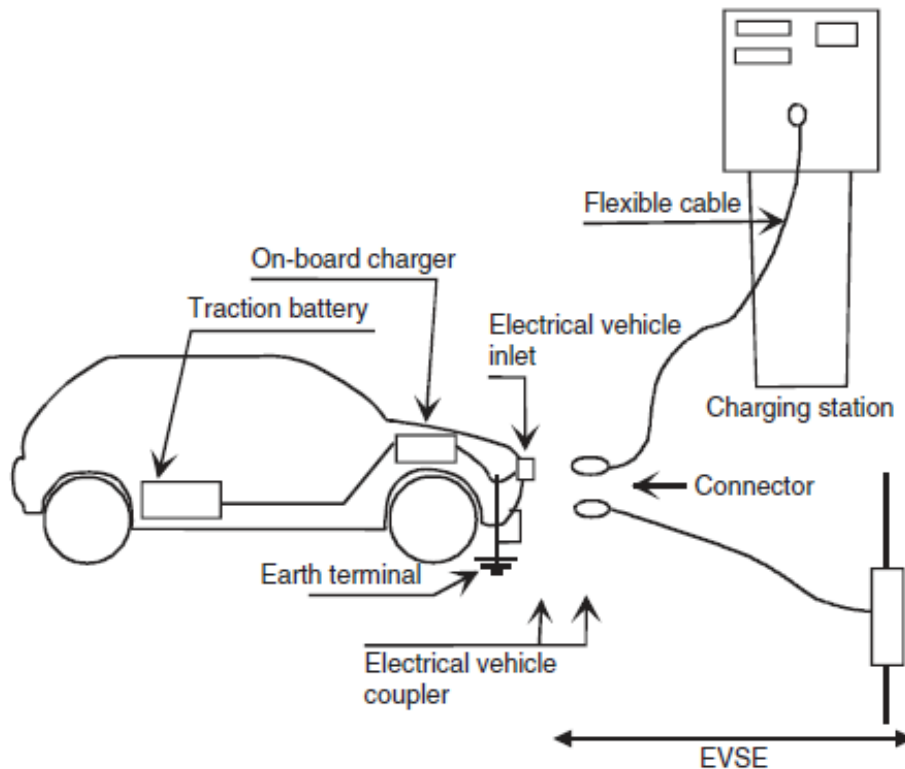
- Case “A” – where the cable and plug are permanently attached to the vehicle. This case is usually found only in very light vehicles (Fig. 44).
- Case “B” – where the cable assembly is detachable and connected to the vehicle with a connector. This is the most common case for normal and semi-fast charging (Fig. 45).
- Case “C” – where the cable and vehicle connector are permanently attached to the supply equipment. This arrangement is generally used for fast charging (Mode 4), so that drivers do not have to carry heavy cables around. Public charging stations using this case are however at a higher risk of copper theft (Fig. 46).



**Figure 44** Case "A" connection.



**Figure 45** Case "B" connection.



**Figure 46** Case "C" connection.

### 5.2.2 Inductive charging

Inductive charging is defined as the transfer of energy from the supply network to the vehicle in an electromagnetic way, using a two-part transformer with the primary connected to the network and the secondary installed on the vehicle. Charging can be performed after juxtaposition of the two parts.

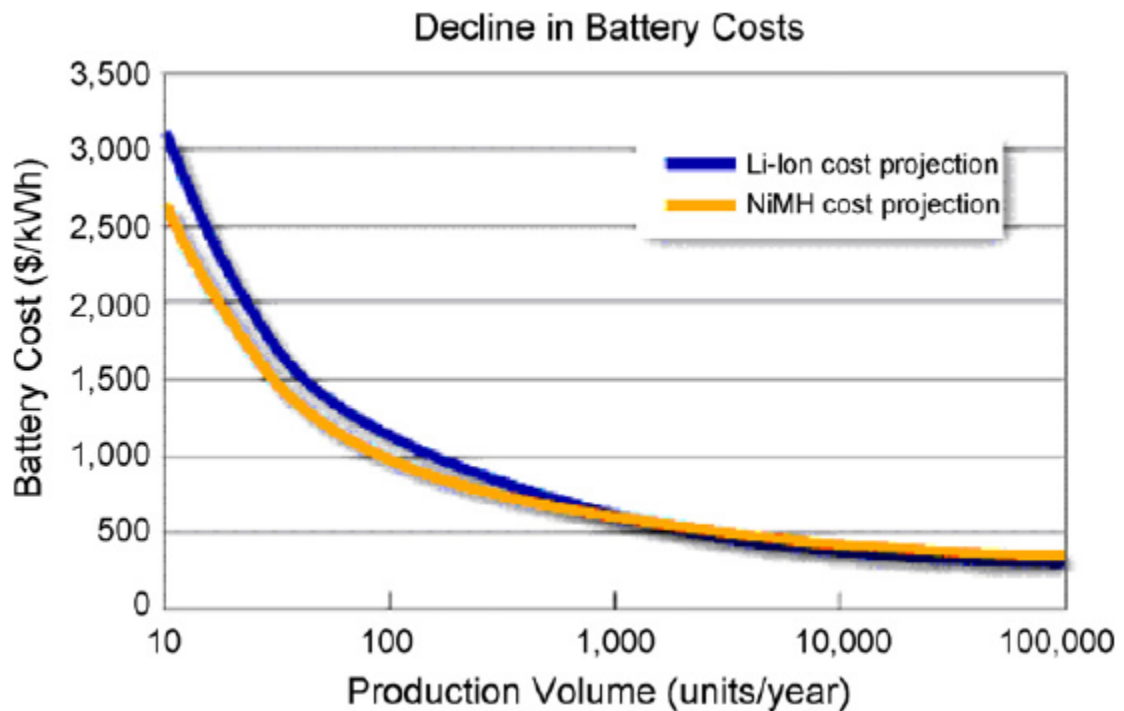
The introduction of inductive charging systems has been proposed to allow a considerable improvement of charging safety. The nonconductive energy transfer virtually eliminates all risk of electric shock for the user. Furthermore, the opportunity for automatic connection dispenses with the use of electric cables, thus removing both electrical (handling of power connectors) and mechanical (trailing cables) hazards which are usually associated with the use of electric vehicle charging equipment.

## 5.3 Economy

Plug-in hybrid vehicle is not considered economical taking into account the extra battery cost. The choice of the right electric range to cover the daily driv-

ing requirements is vital and automobile manufacturers are expected to produce PHEVs with different all-electric ranges for their customers [32]. Good analysis and research will enable buyers to select vehicles that best meet their needs while allowing them to consume less fuel, all the while minimizing the payback period for the increased purchase price. There is no doubt that the increasing gap between electricity prices and petroleum prices will make PHEVs more appealing in the long term. The viability of plug-ins will depend upon cost as well as performance. Although a plug-in hybrid vehicle will in the beginning have a higher price than a conventional vehicle, the degree of difference is certain to lessen with time. Electricity cost is much lower compared to petroleum fuel and also plug-in hybrids can be charged from the grid late at night when electricity prices are even lower. The use of PHEVs would increase electrical demand that could actually be beneficial, because the increased demand would normally occur at night, during off-peak hours. This would permit the utilities to better maintain balance of their electricity production loads, leading to improved operating efficiencies [33].

Battery expense is a major obstacle to the commercialization of plug-ins with extensive electric only range. Battery costs are reliant upon a range of parameters, including type, materials, design and production volume. Battery designs with lower power-to-total energy ratios (kW/kWh) are a configuration more suitable for plug-in hybrid use. Lithium-ion batteries are currently more expensive than Ni-MH batteries. Also as battery technology advances, the plug-in hybrids will be more successful. As production volumes increase, cost will decrease with the introduction of automated manufacturing lines and economies of scale. Fig. 47 shows the trend of reduction in battery cost with increase in production volume [34].



**Figure 47** Battery production volume vs battery cost.

The motor and batteries in these vehicles require very low maintenance over the life of the vehicle. The engine also does not require any more maintenance than in any other IC engine powered vehicle. Because these plug-in hybrids have regenerative braking, brake pairs may even endure longer than those in normal cars. However, as the battery life rises in the future, the costs will come down and the economics gets better. Old batteries must be recycled to down-grade cost on a per-vehicle basis once all transport, processing, and disposal costs are taken into account. Also, power electronics need to be made smaller, simpler and less expensive [32].

#### ***Government support and incentives for the deployment of PHEVs***

The choice of electricity to power the PHEVs of tomorrow is important and large number of factors must be evaluated. This choice needs to consider not only the advanced technology but also the safety and health considerations, overall infrastructure costs, fuel cost on a tax neutral basis and acceptance by the public. The main question is whether there is enough interest on the part of the government and vehicle customers to encourage the industry to commercialize this technology. The following measures can be taken as important steps

by the government to hasten the development and deployment of plug-in hybrid electric vehicles [32]:

- Create an awareness program to the general public on the characteristics of plug-in technology. Moreover, create a program which reaches the university level to educate science and engineering students on all types of electric-drive technology.
- Direct the national research programs to concentrate on increasing the performance of batteries, electric-drive systems, power electronics and related system developments.
- As fleet data becomes available, the government can amass and distribute the operating data suitably and inform the consumers and fleet operators about the benefits of plug-in hybrid technology.
- Point the appropriate regulators to develop a certification test protocol for plug-in hybrid drive systems to maximize the benefits received by the manufacturer and consumer.
- Institute a program with the automotive manufacturers to create prototype demonstrations with a focus on near-term applications.
- Develop a plan for obtaining a fleet of plug-in hybrid electric vehicles in a mixture of configurations to be operated in various locations across the country.

Some of the incentives that could help are [32]:

- A tax reimbursement on the upfront costs of the vehicle due to the cost of the batteries for a few years.
- The auto companies should consent to standardize on some battery parameters that would allow the battery technology to develop, but allow the auto industry to build the vehicles.
- The government should support this type of transportation because it greatly improves the society's transportation efficiency.

## 5.4 Outlook

Several technologies to be implemented in the next generations of automobiles are found on the horizon. There are still a lot of technology challenges to prevail over, particularly in the area of plug-in hybrid electric vehicles. Hence,

the present challenges for researchers are in the development of low weight and high capacity batteries, drives, electronic controls and transmission. Some of these technological challenges are discussed below [32].

#### **5.4.1 Energy storage devices**

Most hybrid hardware subsystems and components with exclusion of energy storage devices have been developed to an acceptable level efficiency performance and reliability. As per the studies, the energy stored in the HEV storage unit is much smaller i.e., in the range of 26.3–77 Wh/kg than that in the EV unit which is in the range of 34.5–140 Wh/kg. It is also clear that the power capacity of the batteries designed for HEVs is much higher i.e., in the range of 77–745 W/kg than those designed for EVs which is in the range of 40–255 W/kg. However, batteries for plug-in hybrid electric vehicles have a requirement for both high energy density and high-power capability based on the driving requirements. Battery attributes for EV and HEV applications are given in Table 10. It is seen from Table 10 that batteries for HEVs are quite different compared with those for EVs in several ways [35]. Furthermore, much less research has been done to develop batteries for plug-in hybrids, but it is possible their characteristics will be intermediate between those of EVs and HEVs. Moreover, recycling of used batteries and the recycling cost on a per-vehicle basis also need to be addressed in future. Other complementary energy storage units including ultra-capacitors and flywheels need to be investigated [32].

**Table 10** Characteristics of various technologies/types of batteries for use in vehicle applications [34].

Battery technology	Application type	Ah	Wh/kg at C/3	Wh/kg 95% eff
<b>Lead Acid</b>				
Panasonic	HEV	25	26.3	77
Panasonic	EV	60	34.5	47
<b>Ni-Mh</b>				
Panasonic	HEV	6.5	46	207
Panasonic	EV	65	68	46
Ovonic	HEV	12	45	195
Ovonic	EV	85	68	40
<b>Li-on</b>				
Saft	HEV	77	77	256
Saft	EV	41	140	90
Shin-Kobe	HEV	4	56	745
Shin-Kobe	EV	90	105	255

The batteries efficiency is affected by a number of factors including temperature, driving patterns i.e., city driving/highway driving, charging patterns, etc. Maintaining optimum, uniform temperature or some means of thermal management is essential to obtain peak battery performance. Under cold temperature conditions, the capacity of the battery may be only at 70% of its rated capacity [36]. For plug-in hybrids, battery cycle life becomes an important concern. The battery will be recharged from a low state-of-charge (after deep discharges) more often than for the battery powered EV. As a result, the battery cycle life requirement for plug-in hybrids will be more challenging than for pure EV. A minimum of 2000–3000 cycles will be required. Hence, both in terms of power and cycle life, the plug-in hybrid application is more challenging for the battery than the EV application [35]. PHEV users would require the battery to last the life of the vehicle. The frequent recharging and overcharging loses its ability to take and hold a new charge. In plug-in hybrids, batteries will be charged up to at least 95% and then deeply discharged during the all electric range of driving before settling into a hybrid mode. Such deep discharging usually reduces battery life. Battery life can be prolonged by increasing the size for a given application, a larger battery will demand a lesser percent discharge than will a smaller bat-



tery and consequently will have a longer life. However, the use of larger batteries would of course increase cost, size and weight [32].

The nickel-metal hydride battery durability, specific power and high temperature operation have improved notably, suggesting that a battery pack enduring for the life of the vehicle may be within reach. Li-ion batteries are a much newer design still seeing major advances. They provide power and energy densities higher than those of Ni-MH, which lead to physical advantages, such as for a given amount of energy storage, Li-ion batteries can take up one-quarter the size of Ni-MH batteries and weigh approximately half as much. But the durability, cost, and safety of Li-ion batteries still need improvement [37]. However, significant research is required to be done before lithium-ion batteries are ready for commercialization to accomplish improved performance, life, tolerance to abusive conditions (such as overcharge) and reduced cost [32].

The first and primary challenge is the validation of battery characteristics capable of meeting PHEV operation requirements. This is a considerable challenge which has been under evaluation for the couple of years, but this work has made astonishing progress. The development of a strong supplier base is an important second challenge. So, it is important to increase the potential pool of component users and component suppliers so that economies of scale can be generated as quickly as possible. The third challenge is the coordination of a safe and usable set of charging standards. Owners need to know that charging their vehicles is as safe and easy as charging their cell phones. This is the easiest challenge to meet from a technical point of view, but it will require active participation from regulators, automotive industry, and electric power industry [32].

Any battery is potentially unsafe when mishandled or subjected to trauma such as physical blows, extremely high temperatures, or fire. Even though a vehicle is safe under normal conditions, a great deal of testing is necessary to verify its safety in a crash or fire. New battery technologies will call for extensive testing before they are considered right and proper for in-vehicle use. Emergency responders must also learn how to handle new vehicle battery technologies safely in the event of a crash or fire [32].

The other significant technical challenges include higher initial cost, cost of battery replacement, added weight and volume, performance and durability. Future challenges will incorporate verifying lifetime testing in field testing, and developing production facilities to ramp up the availability of this technology.

#### **5.4.2 Electric propulsion motors**

In the area of propulsion motor and other motor control technologies, techniques to abolish speed/position sensors, inverter current sensors, etc., have been under investigation for several years. These technologies have not yet been confirmed to be practical for automotive applications [38–44]. Controllers need to be developed for the vigorous operation of all vehicle subsystems. The technology advance struggle needs to be focused on the sensorless operation of electric machines and the reduction or elimination of current sensors in inverters. The development of low cost, high temperature magnets would lead to the extensive use of permanent magnet (PM) motors. PM motors have higher efficiency and need lower current to gain the same torque as other machines. This would decrease the cost of power devices as well. This cost drop is critical for market feasibility. The future technological challenges for the electric motors will be light weight, wide speed range, high efficiency, maximum torque and long life [32].

#### **5.4.3 Power electronics**

The power switching devices and associated control systems and components perform a key role in introducing plug-in hybrid vehicles to market with reliability and affordability. The power electronic system should be efficient to improve the range of the electric operation and fuel economy. The selection of power semiconductor devices, converters/inverters, control and switching strategies, the packaging of the individual units, and the system integration are essential to the development of efficient and high performance PHEVs. Additionally to power devices and controllers, there is a number of other components such as capacitors, inductors, bus bars, thermal systems that form a major portion of a power electronic unit. The packaging of all these units as one system has major challenges. To meet the needs of the automotive environment, sev-

eral technical challenges need to be conquered, and new developments are necessary, from the device level to the system level [45].

The technologies related to device packaging must be investigated by the semiconductor industry to develop a power switch. Technologies such as top-side power connection without wire bonds, minimizing wire bonds, dynamic matching, heat-sinking both sides of the die, direct bond copper on alumina and aluminum-nitride substrates, interconnect solutions for large-scale manufacturing, etc., must be investigated too. Wire bonding, device interconnections, etc., are the obstacles to the development of high-current-density power units. The reliable operation of power modules and other related packaging technologies needs to be examined. The capacitors with high-frequency and high-voltage operations, low equivalent series resistance, high operating temperatures, and high ripple current capabilities need to be further developed. The power electronic systems accessible in the market are still hulking and difficult to package for automotive applications. Hence, improved dielectric materials need to be investigated. The technology of laminated bus bars with high isolation voltage and low inductance needs more work to meet the automotive operating environment [32].

Consecutively to meet the packaging objectives, the components must be planned to operate over a much higher temperature range. An innovative way of cooling the full unit needs to be researched to quickly take away the heat from the devices. The current heat management techniques are insufficient to dissipate heat in high-power density systems. Moreover, the impact of current intensiveness in a system on lower efficiency, larger passive components such as inductors and capacitors, and a thicker wiring harness among the components should be correctly taken into consideration at the stage of system design. Also there is a need to develop an inverter topology that achieves the performance of a soft-switched inverter but with less components and simplified control. Topologies with two or more integrated functions such as an inverter, a charger, and a dc/dc converter and with minimum use of capacitors need to be developed. In the area of dc–dc converters, further development is needed to obtain 12 V from 42 V and higher voltages [32].

#### **5.4.4 Other technological challenges**

Diminishing the energy consumption at the vehicle systems' level must be achieved by dropping weight, aerodynamic drag, rolling resistance and emission characteristics through the use of light materials, aerodynamic vehicle designs, advanced technologies that can decrease the friction and improved system efficiency. Therefore these technologies offer energy management advantages while helping maintain the cost of fuel efficiency reasonably priced to the customer [32].

##### ***Aerodynamics and low resistance tyres***

Manufacturers are now focusing on aerodynamic drag and tyre rolling resistance for improved aerodynamics and consequently reduce fuel consumption, environment noise and additionally provide the driver with more control and stability. Wind resistance can be reduced through redesigning the body to a more aerodynamic shape. Furthermore, the use of slippery body panels can further decrease the aerodynamic drag. An additional way to improve efficiency is to decrease rolling resistance caused because of the friction between wheels and road. Rolling resistance can be limited through the use of low resistance advanced design tyres [46].

##### ***Light weight materials***

An effective way to enhance energy efficiency is to decrease the overall weight of the vehicle. Consequently, the use of advanced materials with high strength to weight ratio, such as composite or plastic body panels, light weight aluminum structural components can also upgrade safety while reducing weight, if more sophisticated structural designs are used. The development of injection-molded thermoplastic vehicle body technology decreases weight while reducing the cost below that of a conventional steel body and far below other light weight materials such as aluminum, titanium or thermo-set composites. The body system is calculated to weigh 46% less and 15% less costly to manufacture than comparable steel body [47].

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